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MANNED INTEGRITY TESTING OF THE U.S. COAST GUARD CHEMICAL RESPONSE SUIT

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16. Abstract

This report describes manned integrity testing of the U. S. Coast Guard's Chemical Response Suit designed for hazardous chemical spill response. Lawrence Livermore National Laboratory developed a test protocol for measuring the dynamic integrity of totally encapsulating chemical protective suits. This protocol involves the use of both Freon[R] and aerosol challenge agents for measuring suit 'intrusion coefficients' during an exercise routine. In the test, a subject wearing the encapsulating suit and a self-contained breathing apparatus, exercises for 30 minutes while the internal and chamber concentrations of the challenge agents are measured. Intrusion coefficients are measured by ratioing the concentrations of the challenge agent inside and outside the suit. Also pressure inside the suit is measured during the test.

Lawrence Livermore National Laboratory tested the integrity of several Coast Guard Chemical Response Suits. Intrusion coefficients ranging over 10,000 and internal suit pressures from 0.1 to 7.0 inches water pressure (gauge) were observed. This testing was useful in identifying design problems for early prototypes of the Chemical Response Suit. Keywords:

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TABLE OF CONTENTS

Introduction

In our report, "TECP Suit Test Protocol for USCG/USFA Project," we discussed the general design of a totally encapsulating chemical protective (TECP) suit and the test method we have developed to evaluate performance of the TECP suit. In this report, we will summarize the results from our test on the new U.S. Coast Guard's TECP suit made from Teflon-coated Nomex fabric (Figure 1).

Human Subjects Approval

The Lawrence Livermore National Laboratory (LLNL) is operated by the University of California for the U. S. Department of Energy (DOE). DOE requires that all experiments involving human volunteers at LLNL must be reviewed and approved by the Human Subjects Committee. The experimental test procedures described in this report have been reviewed and approved by the Human Subjects Committee.

Experimental Description

Freon Leak Detection System

To measure TECP suit leak rates accurately, a separate gas (Freon 12) and aerosol [polyethylene glycol molecular weight 400 (PEG 400)] detection system is used. The Freon 12 subsystem uses a man-test chamber concentration of 1000 ppm as determined by a Wilks Model 1A infrared spectrophotometer. The interior of the TECP suit is monitored for Freon 12 intrusion using a Varian Model 2700 gas chromatograph (GC) equipped with an electron capture detector (ECD). The sampling time for the GC sampling loop is two minutes. In an upgrade of this system, a second sampling loop

and ECD detector is being added. Thus, by alternating the sampling cycles, a sample can be collected approximately every minute. Since the GC/ECD detection limit for Freon is 0.01 - 0.001 ppm, this measurement technique enables the Safety Science up (SSG) to measure a suit intrusion coefficient of 100,000 to 1,000,000.

Aerosol Leak Detection System

The aerosol concentrations in the man-test chamber and within the TECP suit were measured using a Phoenix Precision Instrument's Model JM 7000 forward light-scattering photometer. The test aerosol of PEG 400 was generated using a Laskin nozzle generator which created a mass median aerosol diameter of approximately 0.68 µm, $\sigma_g = 2.10$. Aerosol concentrations within the man-test chamber were 25 ± 5 mg/m^3. A sample of two liters per minute was withdrawn from the suit and passed through the photometer, providing a real-time measure of aerosol concentrations within the suit.

Suit Modifications

Sample line penetrations into the TECP suit would normally take advantage of existing penetrations for such things as airline cooling or communication. Since no penetration was available in the U.S. Coast Guard TECP suit, we cut a hole in the suit to enable the mounting of a sealed sampling line. The hole was located in a reinforced section in the front waist area of the suit. We used the minimum number of connections necessary to connect the sampling line to the proper monitoring instrument with a minimum length of sampling line. During the TECP suit test, samples of both Freon 12 and PEG 400 were taken simultaneously and used to determine TECP suit performance.

Exercise Protocol

A series of light exercises were chosen to stress the suit in a manner similar to typical work routines. Each of the following exercises was carried out for two minutes, completing the prescribed number of repetitions. The exercises were carried out in the Safety Science Group's man-test chamber (Figure 2).

- o Stand in place.

- o Raise and lower hands from waist to above the head, completing at least 15 raising motions per minute.

- o Walk in place, completing at least 15 raising motions of each leg per minute.

- o Perform deep knee bends, making at least ten complete standing and squatting motions per minute.

- o Touch the toes, making at least ten complete motions of the arms from above the head to the toes per minute.

- o Repeat complete exercise series.

- o Exit man-test chamber.

The exercise series required approximately 20 minutes plus donning and doffing time. A 30-minute SCBA bottle provided enough experimental time, but we used a 60-minute bottle because of its additional weight and duration.

Internal Pressure Monitoring

The pressure inside the TECP suit was measured using a Validyne model, P24 pressure transducer with a range of ±15" water gauge (wg) and an accuracy of ±0.08" wg.

Vent Volume Monitoring

The volume of air exhausted from the TECP suit was measured using a Kurtz Instruments, Inc. flow meter equipped with a probe for Model 505 that was placed in a specially designed tube.

Data Analysis

The output from the photometer, GC/ECD, infrared spectrophotometer, pressure transducer, and flow monitor was collected on a DEC LSI 11/23 lab computer at a sampling rate of 250 ms per entry. Suit intrusion coefficients[1] or protection factors were calculated for both aerosol and Freon 12 test agents. Graphic output from the computer was plotted as the concentration of aerosol penetrating the suit interior (suit penetration) during the various exercises. Real-time pressure and flow traces throughout the various exercises were also recorded. The actual results are presented in the Experimental Results Section and a discussion of their meaning is presented in the Discussion and Conclusion Sections.

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1 $\text{Intrusion Coefficient} = \dfrac{\text{Outside Concentration}}{\text{Interior Suit Concentration}}$

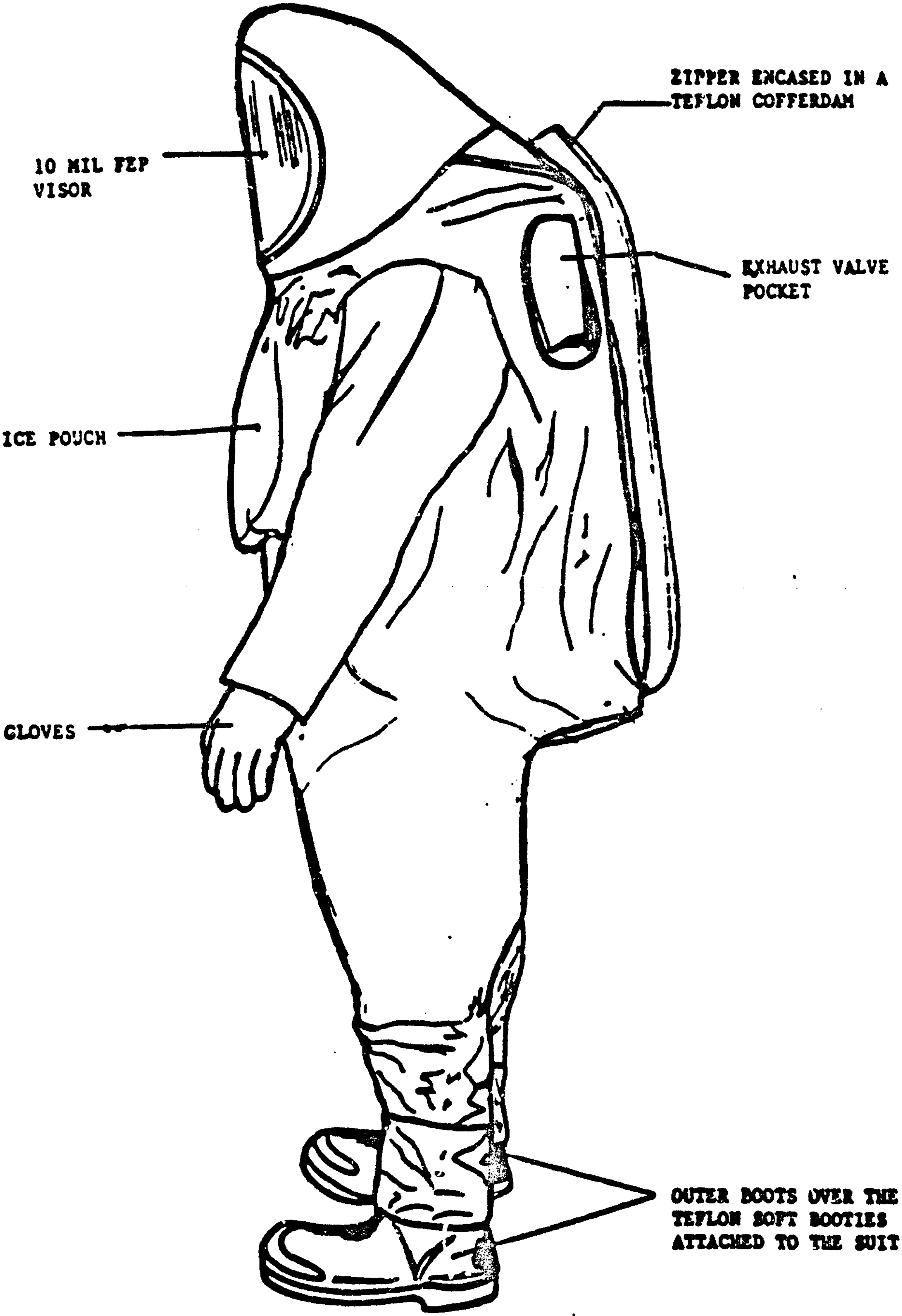
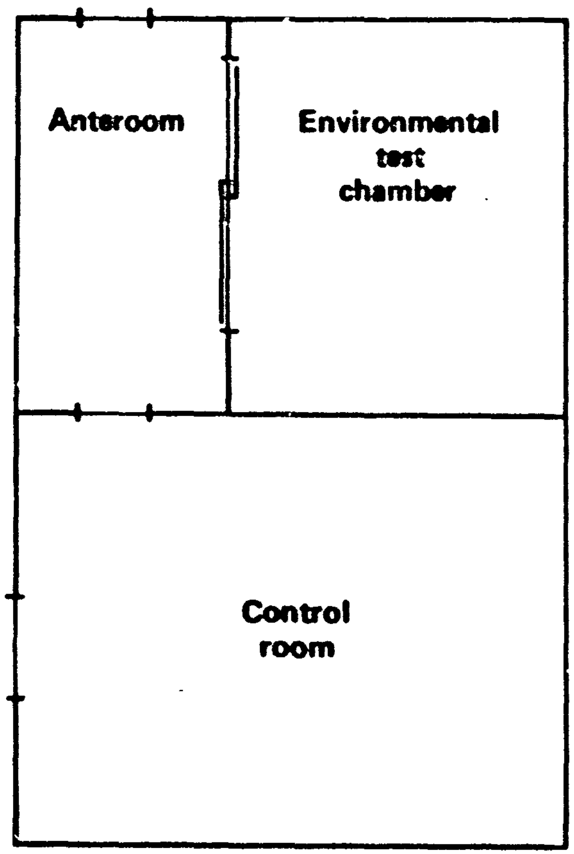


Figure 1. United States Coast Guard's totally encapsulating chemical protective suit design.



Test atmospheres:
Freon™ 12 (gas)
PEG 400 (aerosol)

Stress testing:
Treadmill

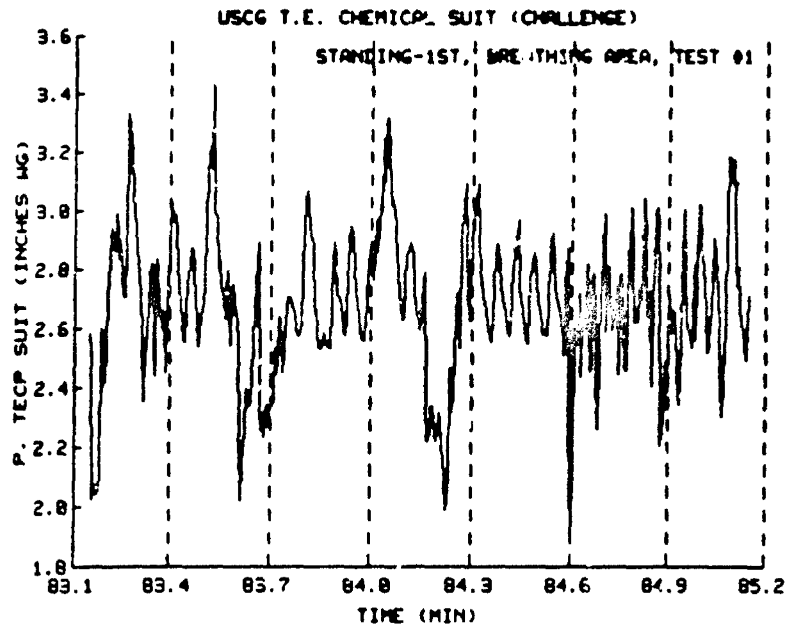
Monitoring:
- GC with electron capture detectors
- IR
- Photometer
- Optical particle sizer
- Size/charge particle counter
- Humidity monitor
- Air flow monitor
- Pressure monitor
- Heart rate monitor

Computer interface:
- DEC LSI 11/23

Figure 2. Saftey Science Group man-test chamber.

Experimental Results

Figures 3 - 39 and Table 1 present the various experimental parameters recorded during each of the three test runs. Due to startup conditions and monitoring or recording failures, some experimental parameters were not recorded. All of our experimental data is presented here; nothing has been omitted by the investigator.



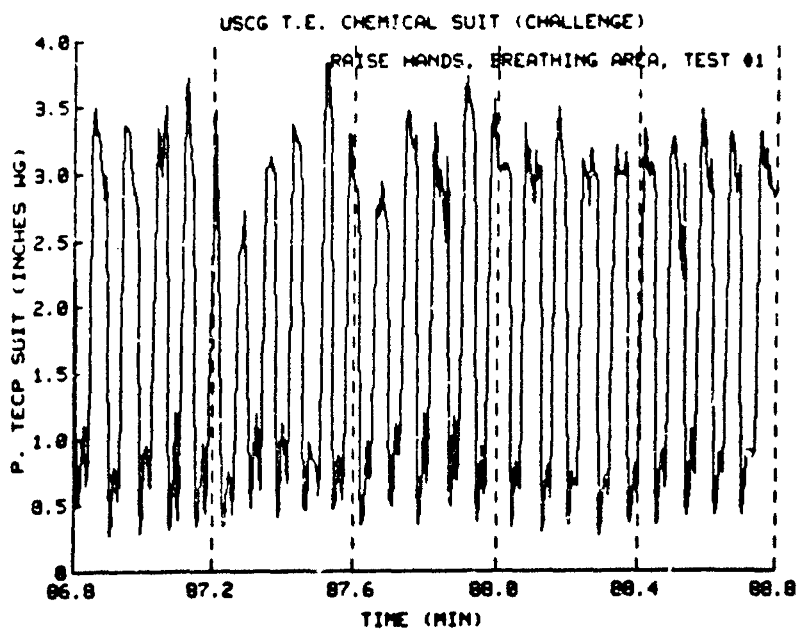
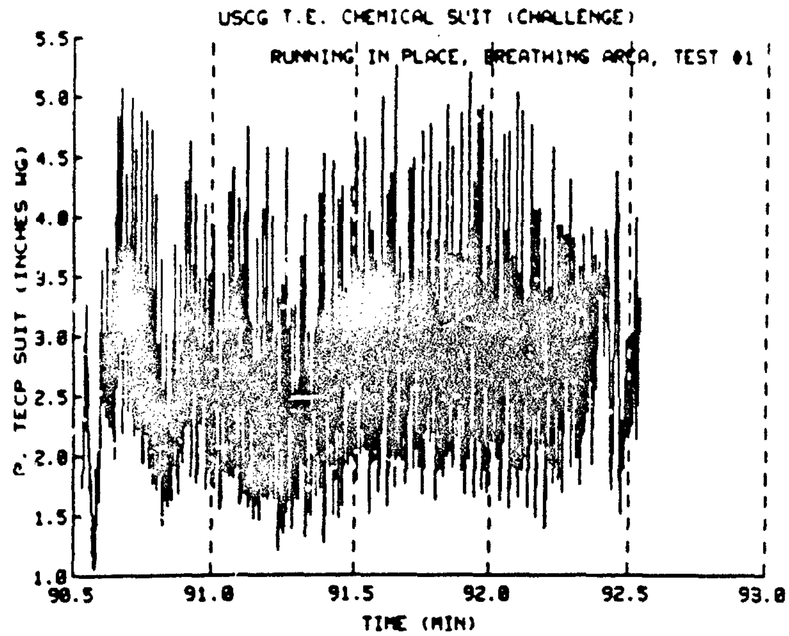


Figure 3. Internal TECP suit pressure for standing in place and rasing the hands above the head.



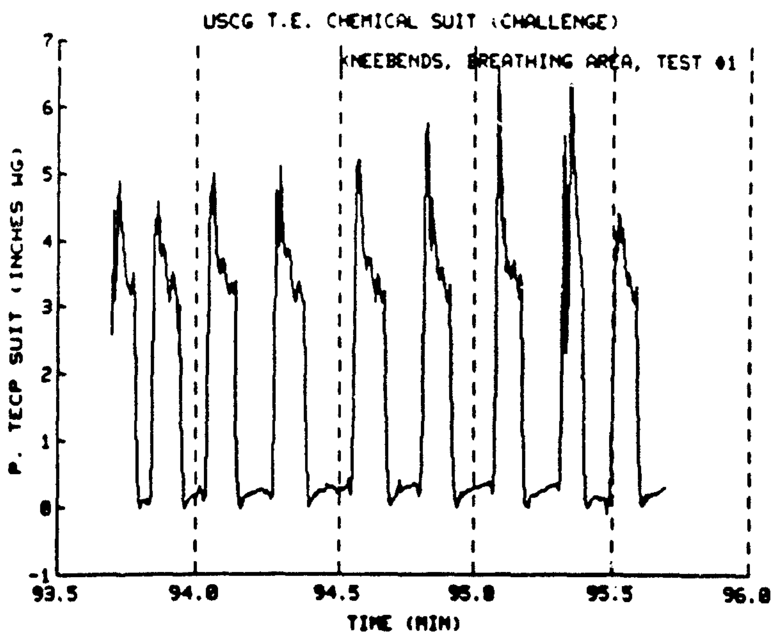
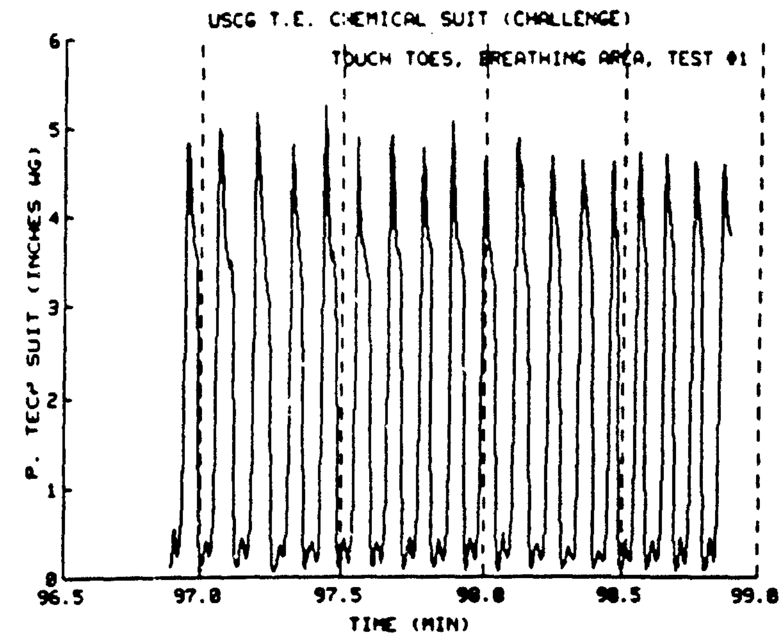


Figure 4. Internal TECP suit pressure for running in place and during kneebends.



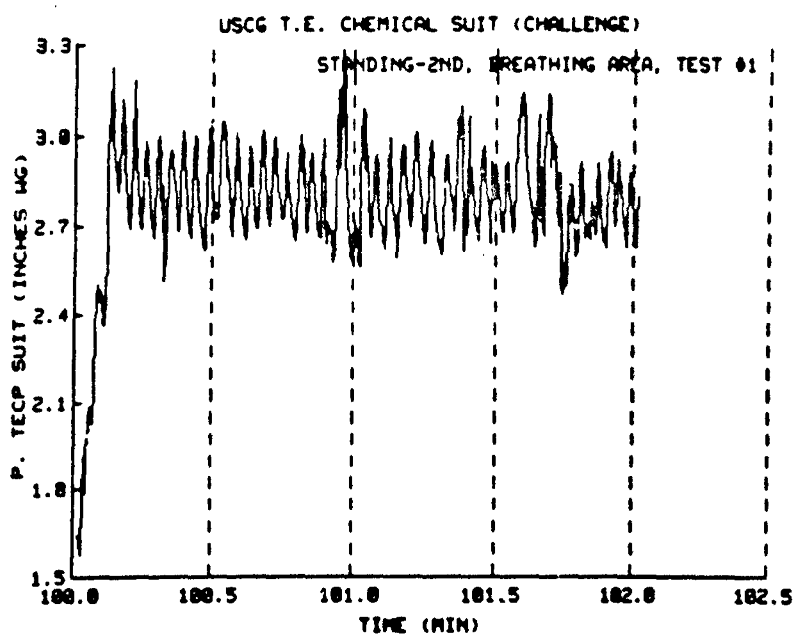
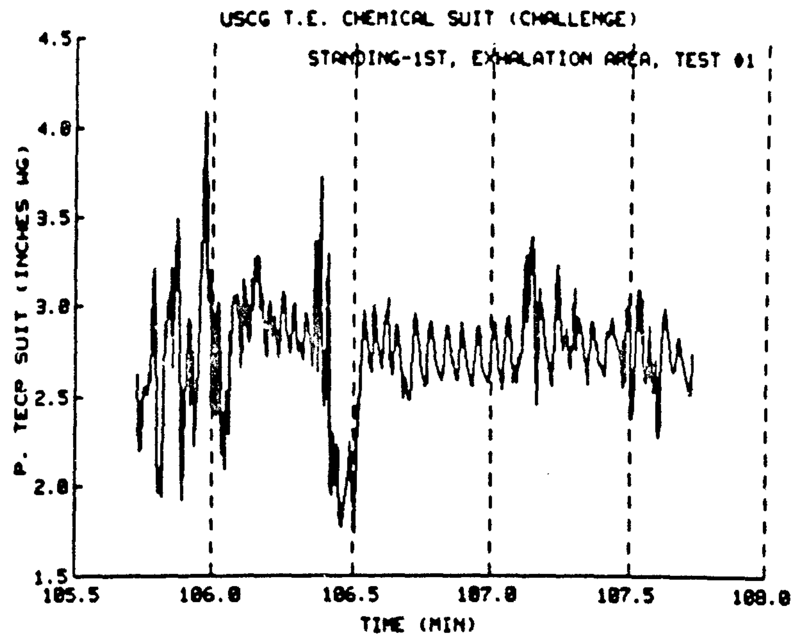


Figure 5. Internal TECP suit pressure for touching the toes and standing in place.



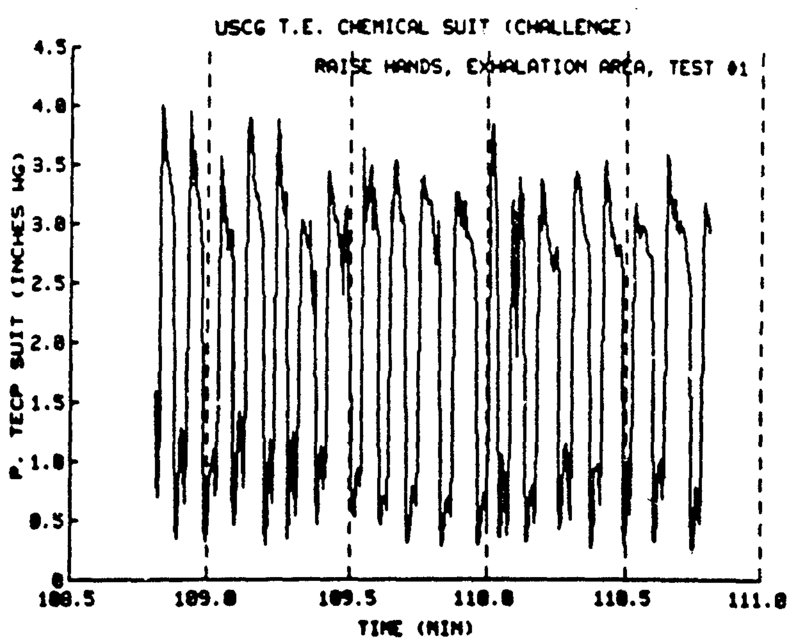
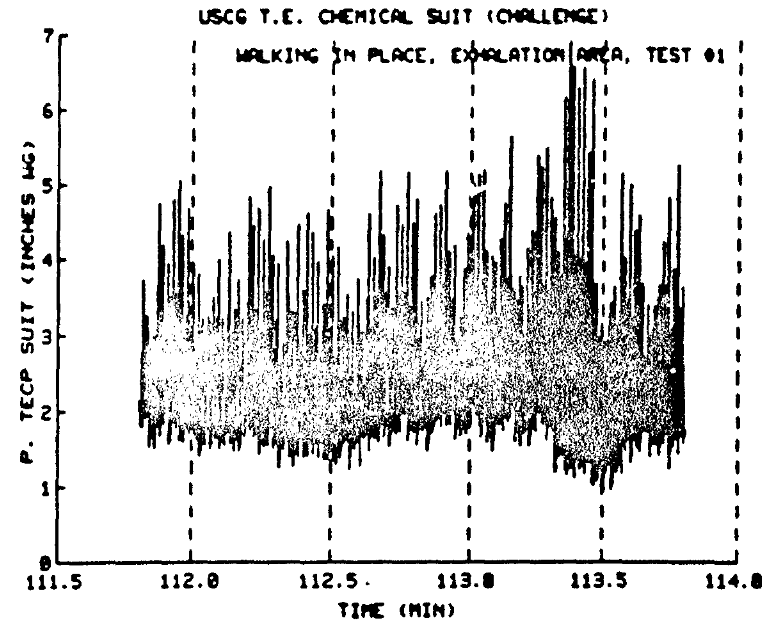


Figure 6. Internal TECP suit pressure for standing in place and rasing the hands above the head.



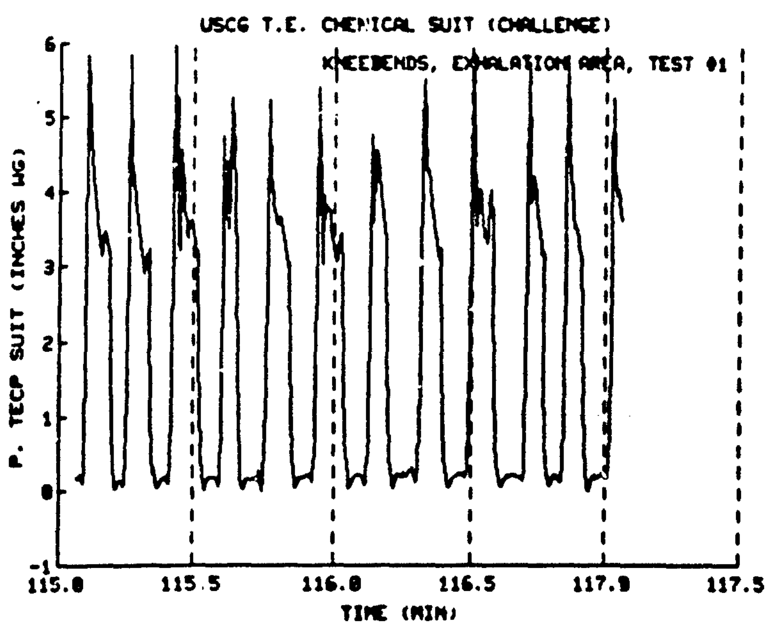
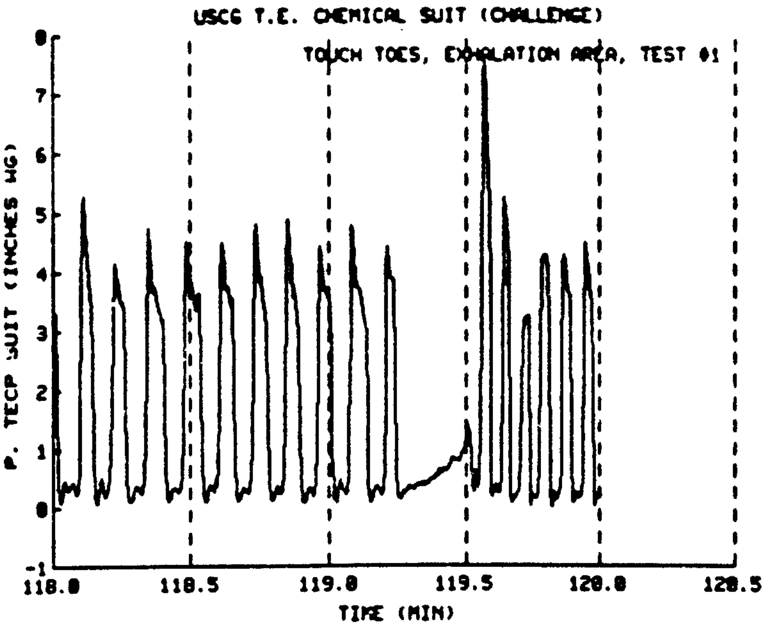


Figure 7. Internal TECP suit pressure for walking in place and during kneebends.



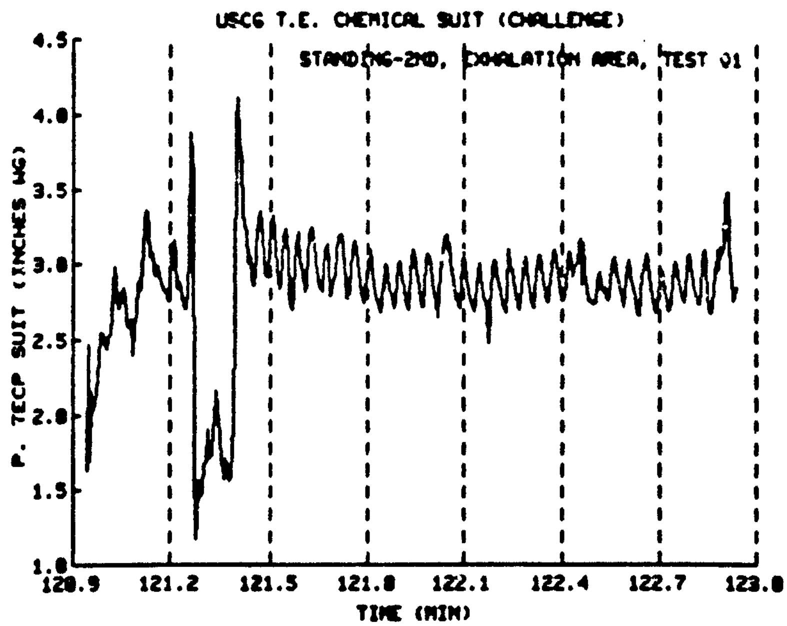
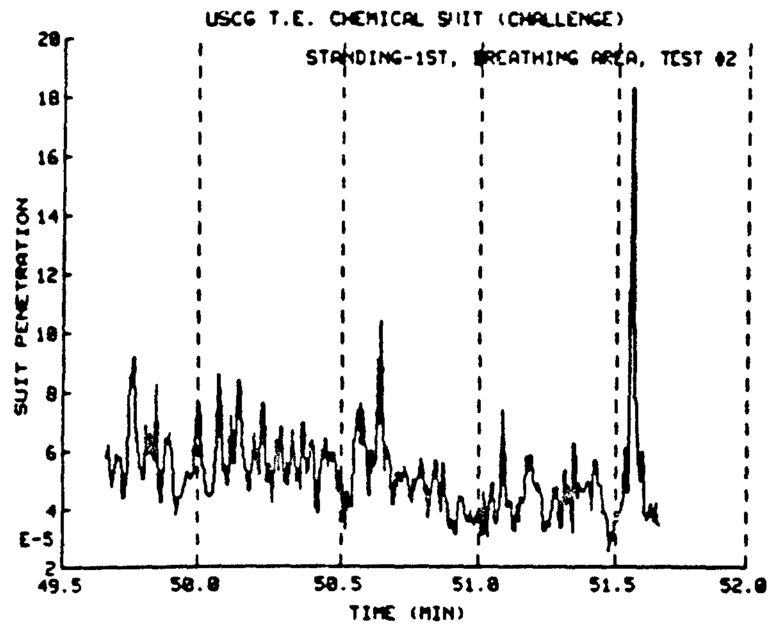


Figure 8. Internal TECP suit pressure for touching the toes and standing in place.



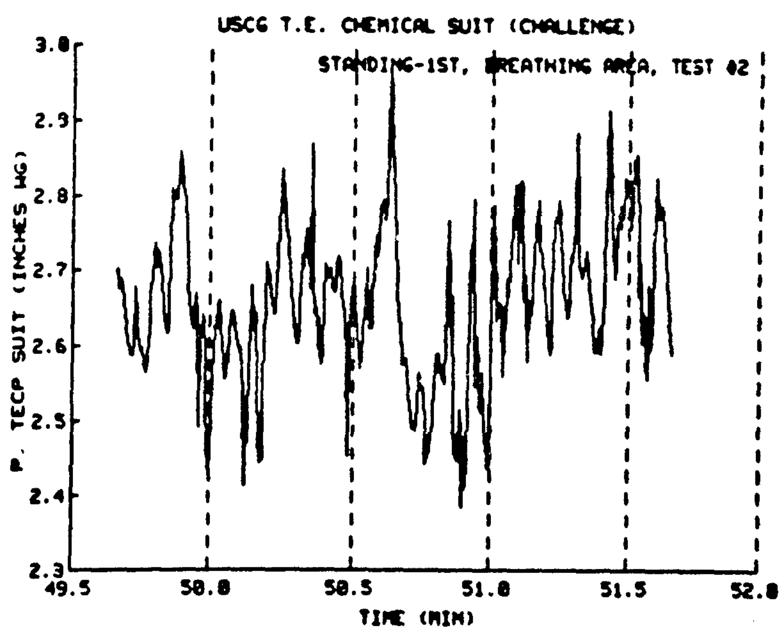
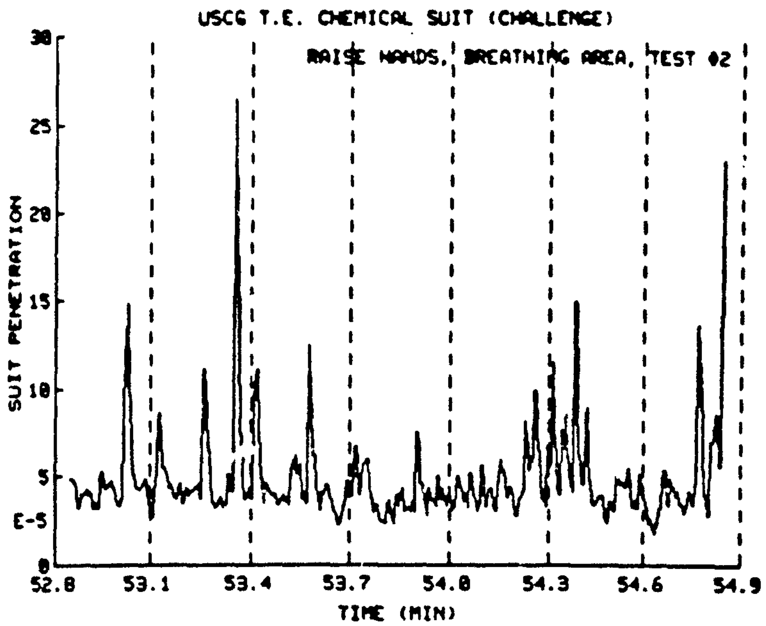


Figure 9. TECP suit aerosol penetration (BZ) and pressure plots for standing in place.



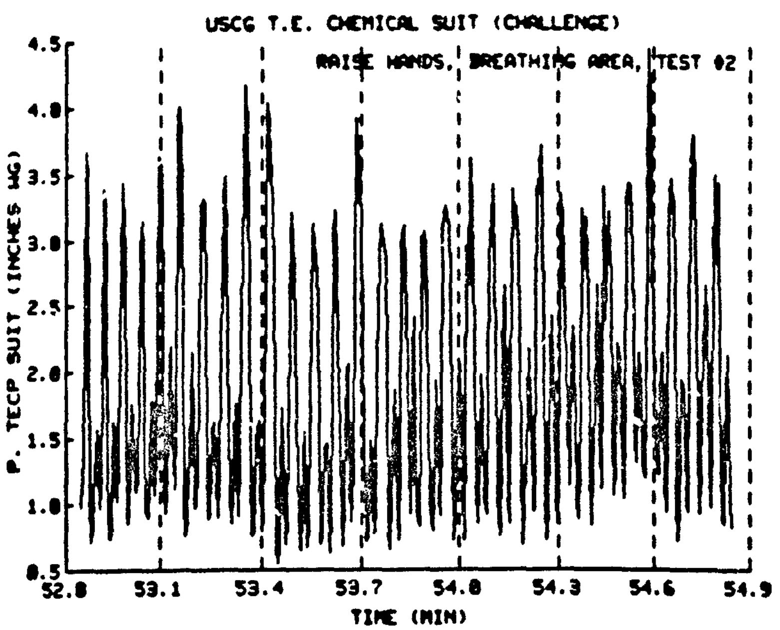
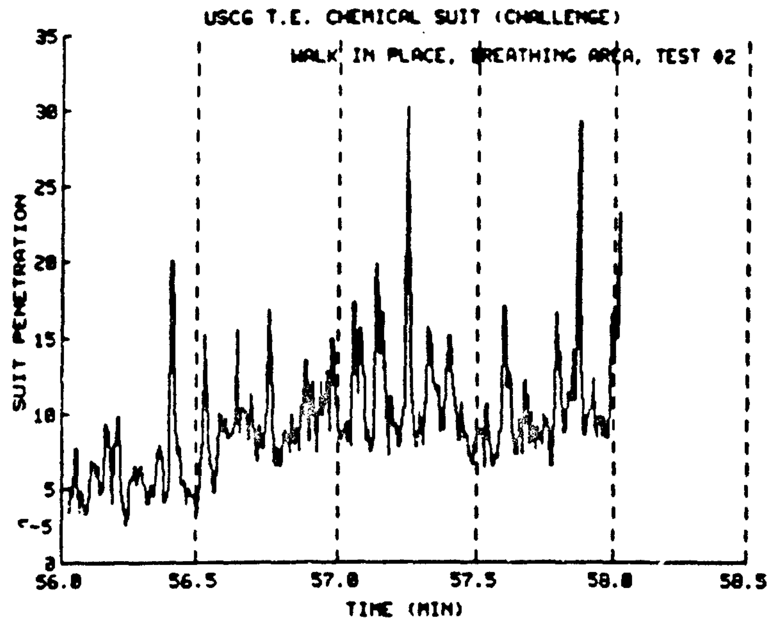


Figure 10. TECP suit aerosol penetration (BZ) and pressure plots for rasing the hands above the head.



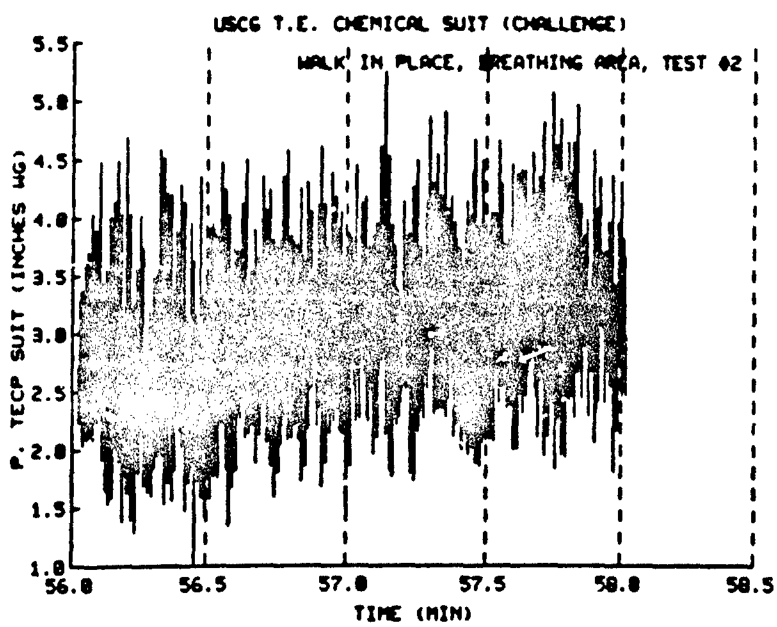
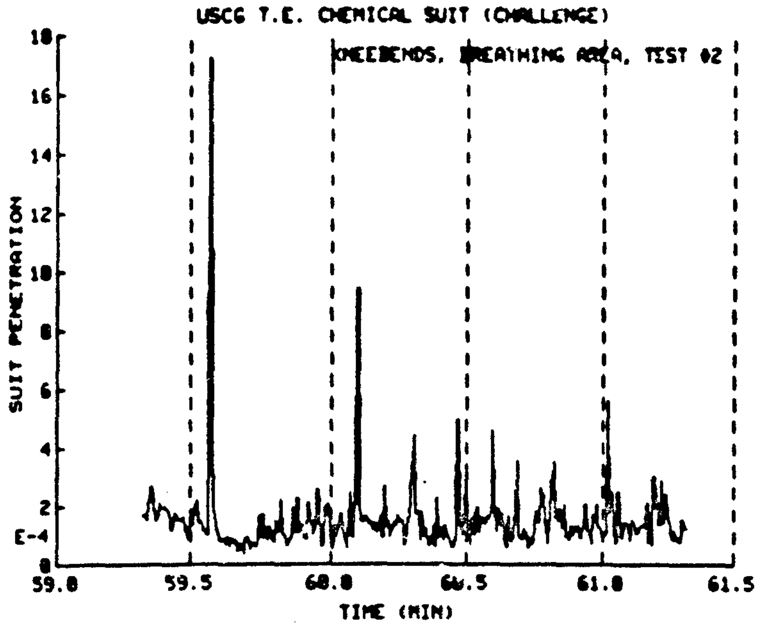


Figure 11. TECP suit aerosol penetration (BZ) and pressure plots for walking in place.



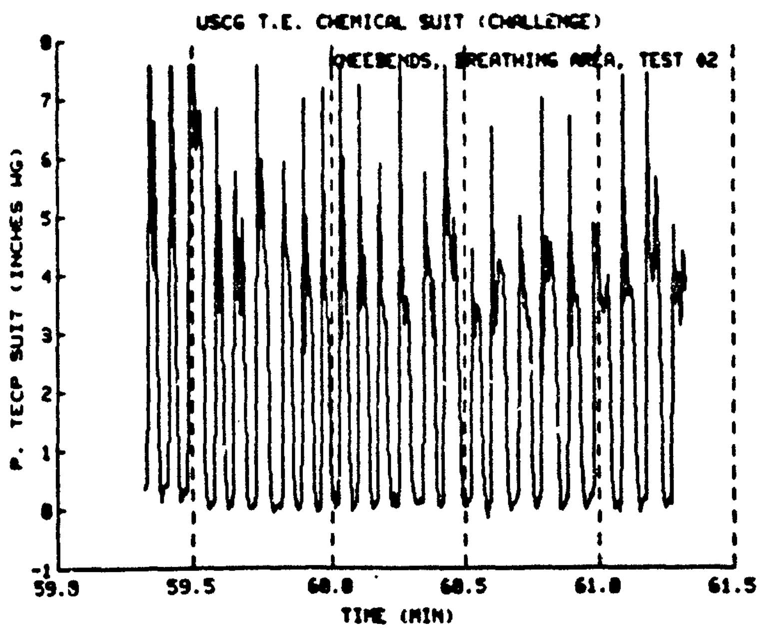
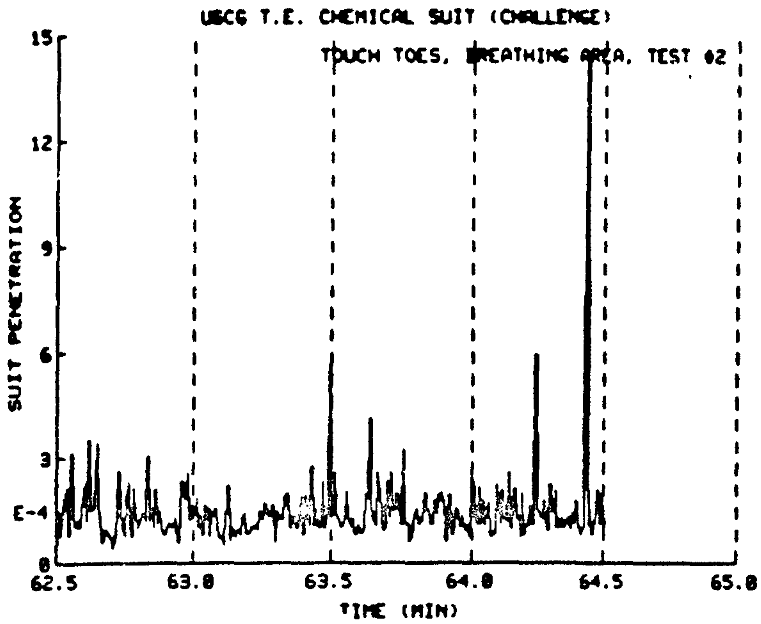


Figure 12. TECP suit aerosol penetration (BZ) and pressure plots during kneebends.



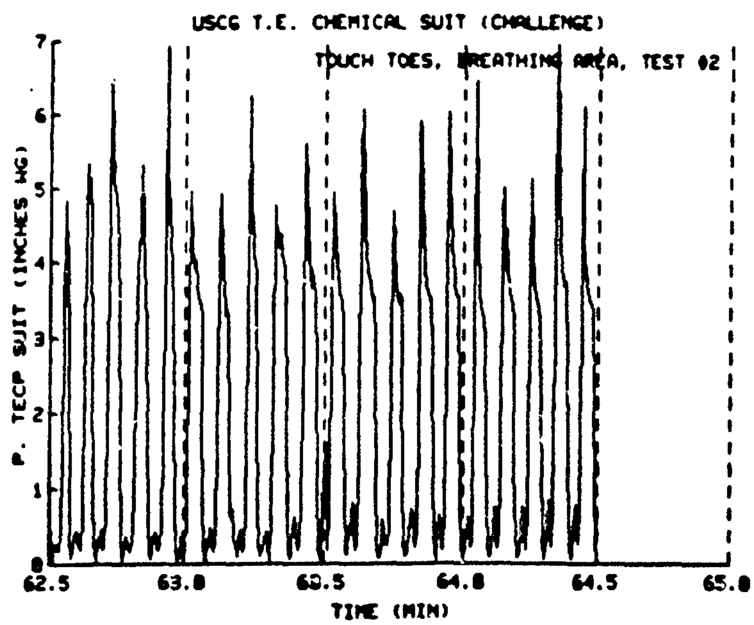
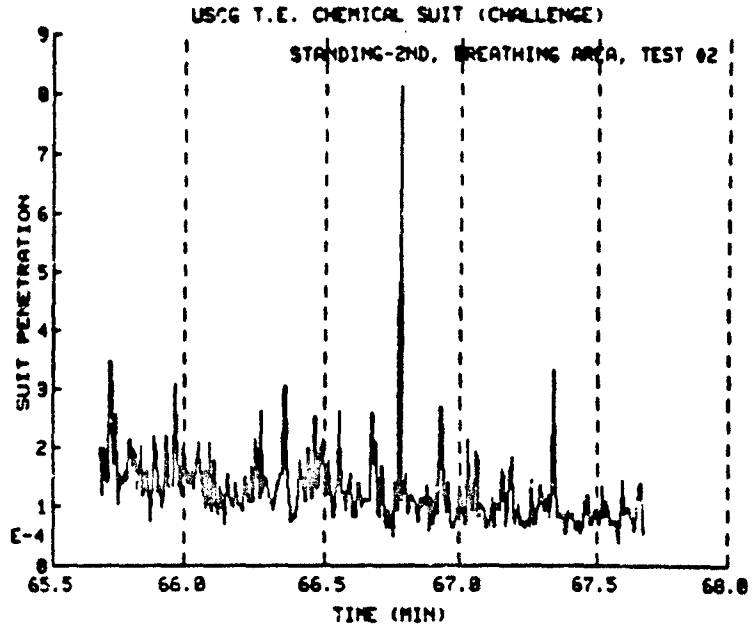


Figure 13. TECP suit aerosol penetration (BZ) and pressure plots for touching the toes.



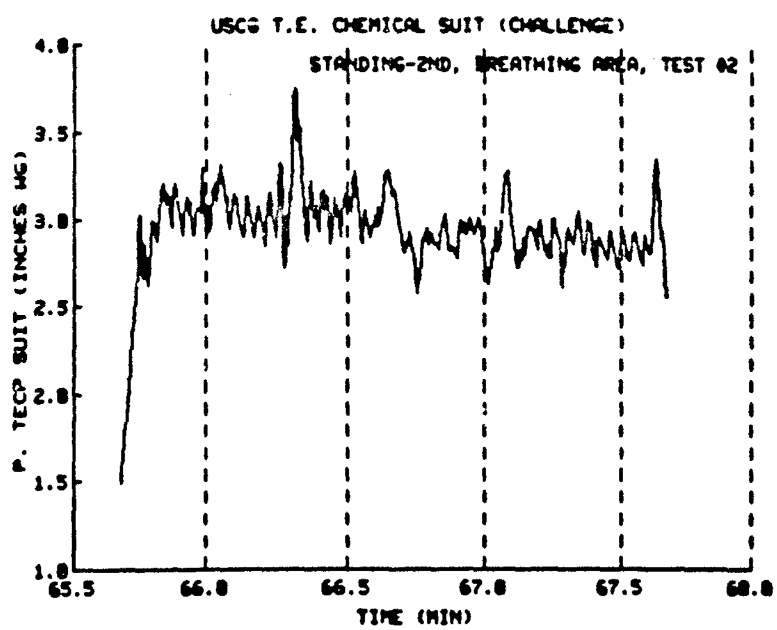
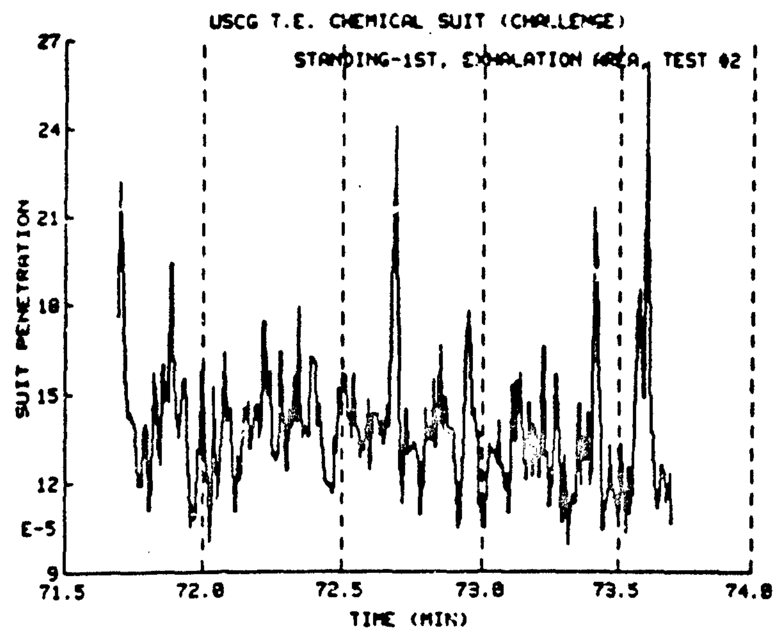


Figure 14. TECP suit aerosol penetration (BZ) and pressure plots for standing in place.



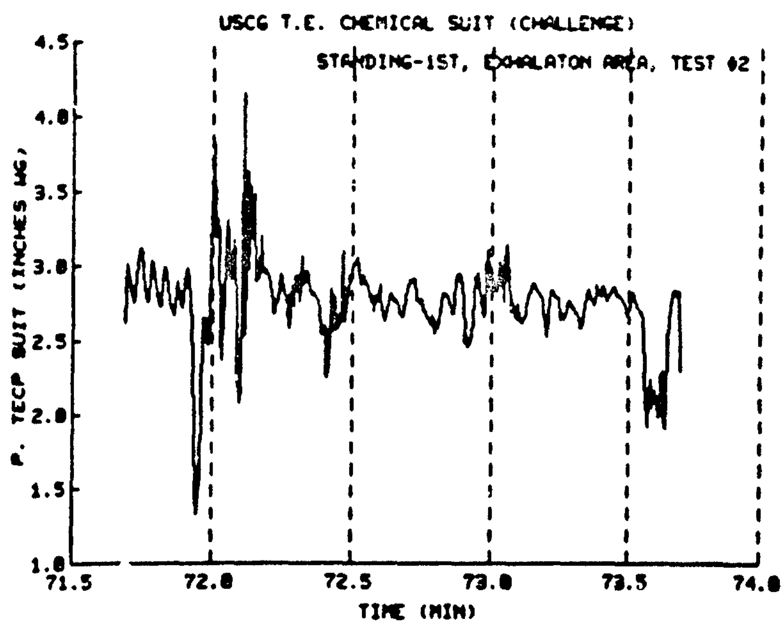
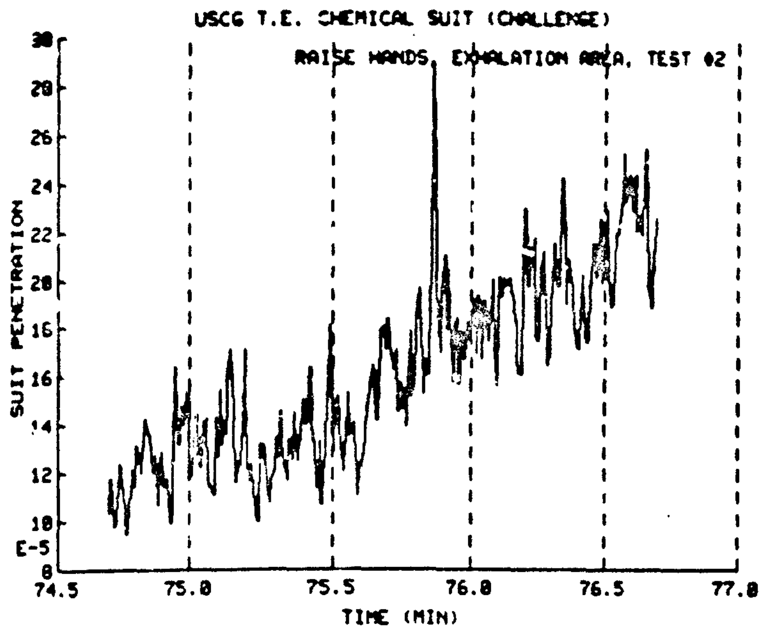


Figure 15. TECP suit aerosol penetration (VVZ) and pressure plots for standing in place.



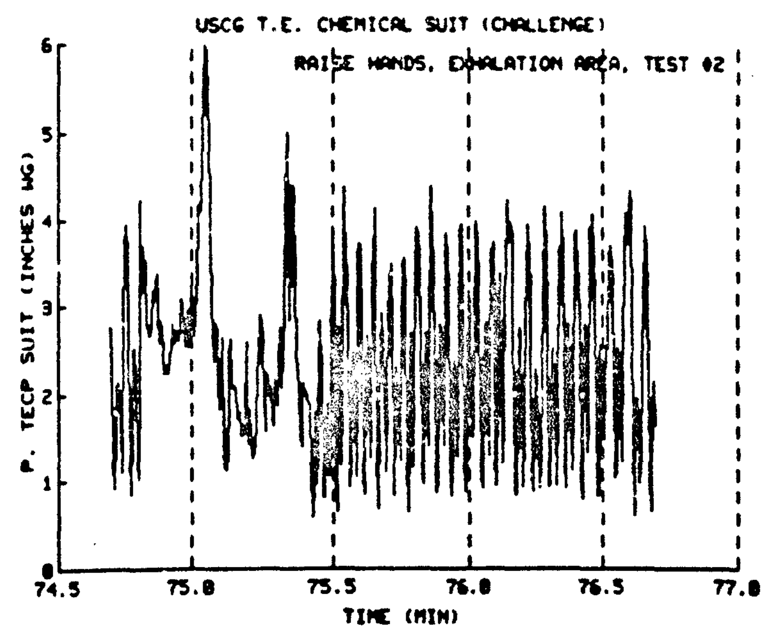
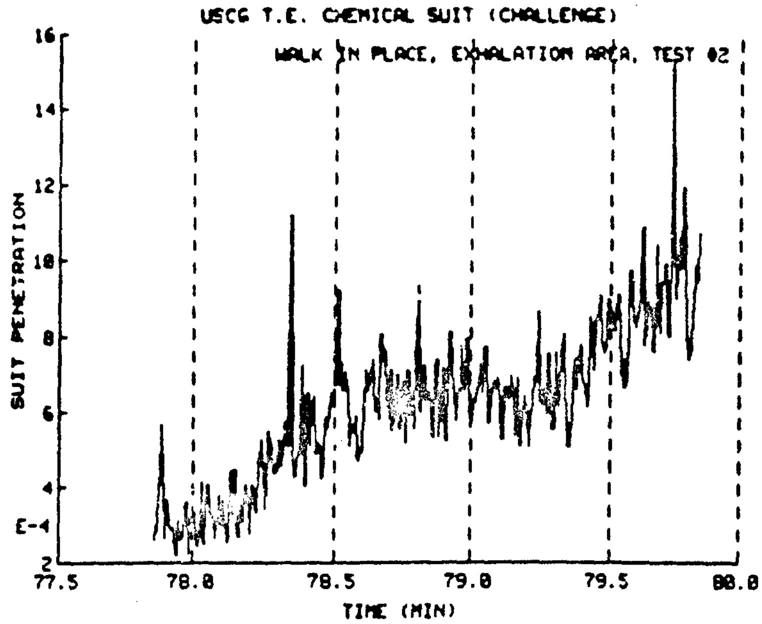


Figure 16. TECP suit aerosol penetration (VVZ) and pressure plots for raising the hands above the head.



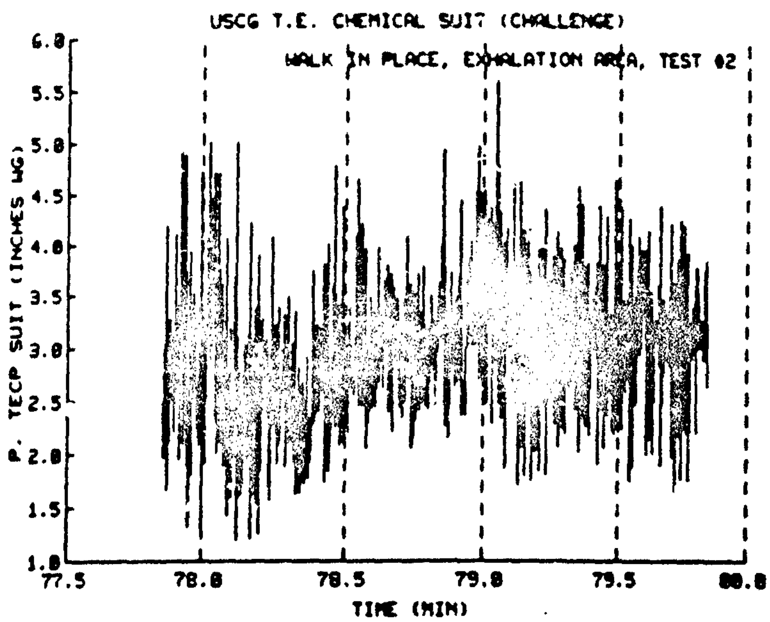
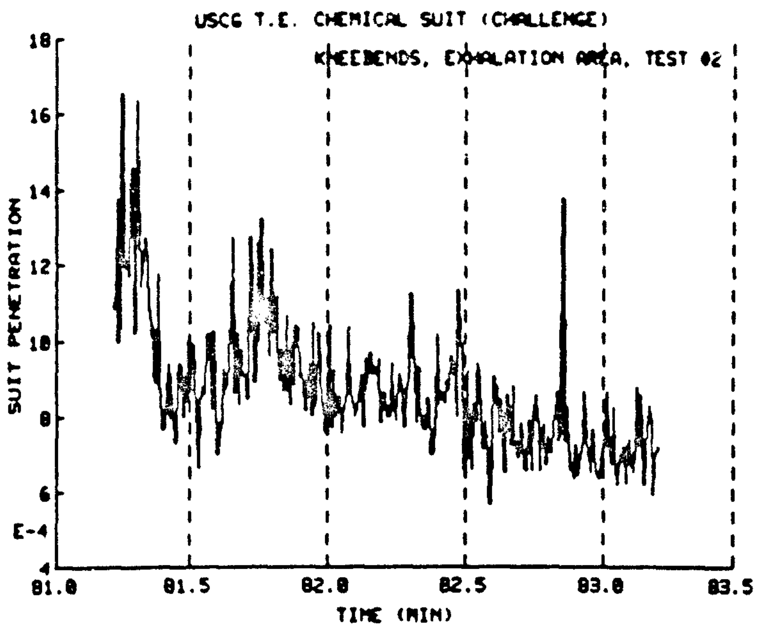


Figure 17. TECP suit aerosol penetration (VVZ) and pressure plots for walking in place.



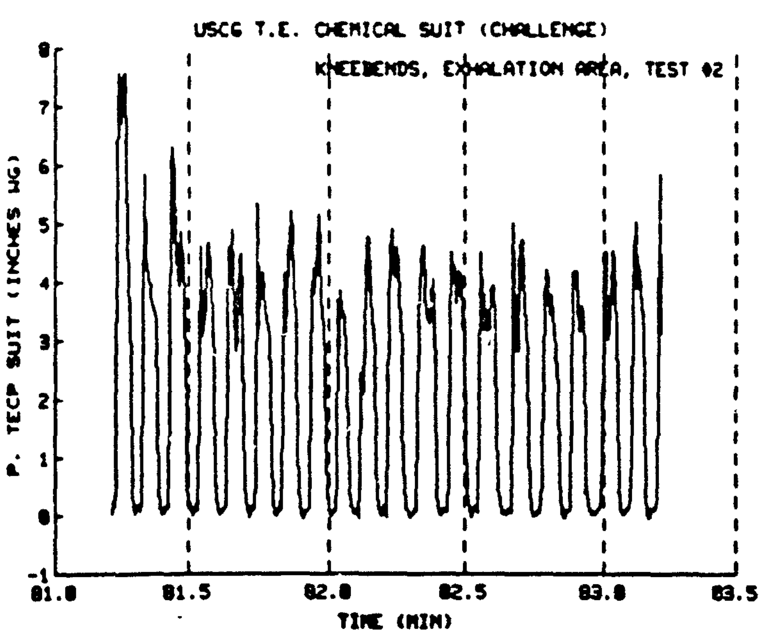
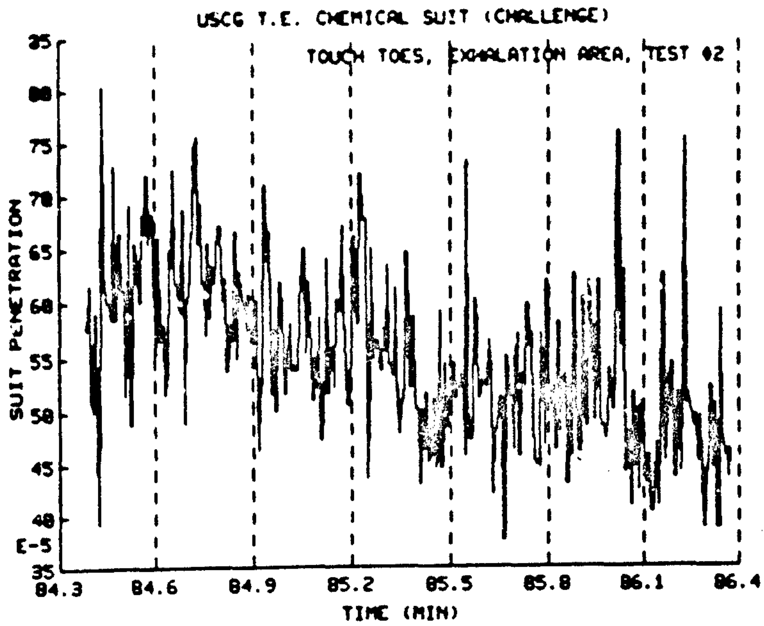


Figure 18. TECP suit aerosol penetration (VVZ) and pressure plots during kneebends



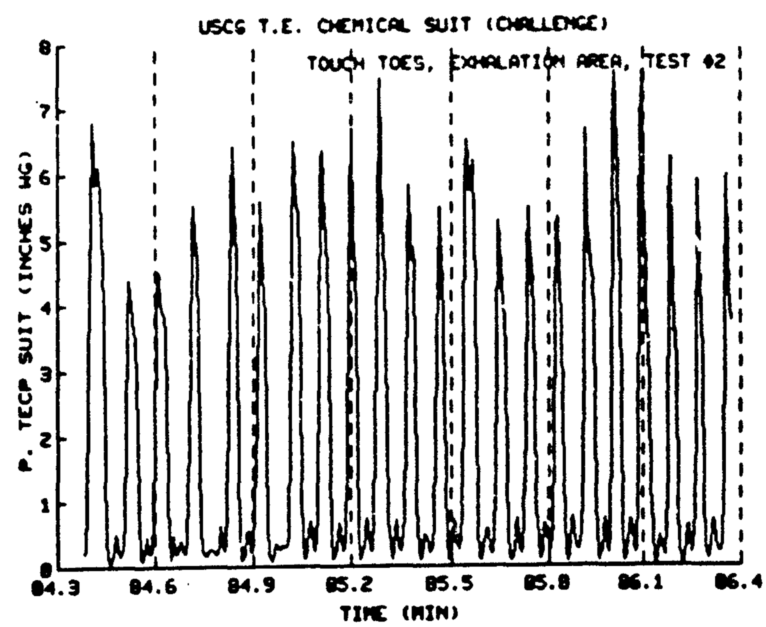
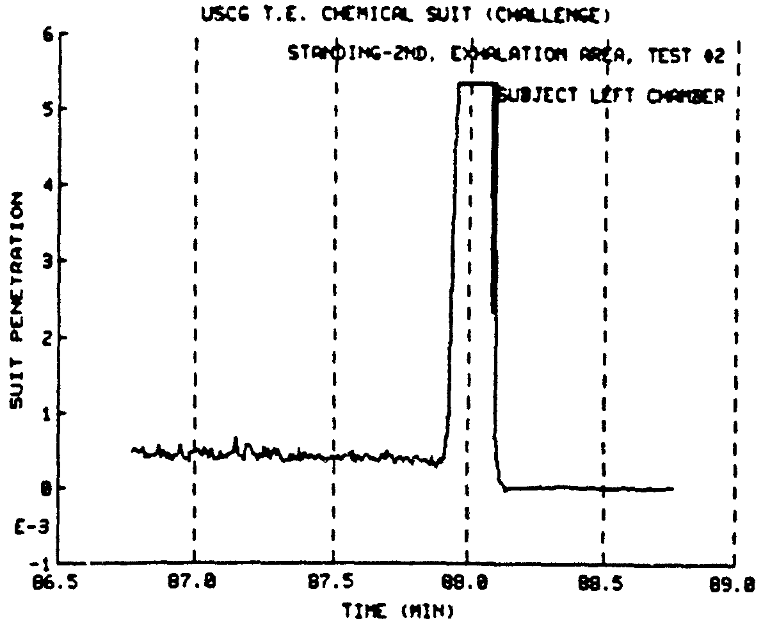


Figure 19. TECP suit aerosol penetration (VVZ) and pressure plots for touching the toes.



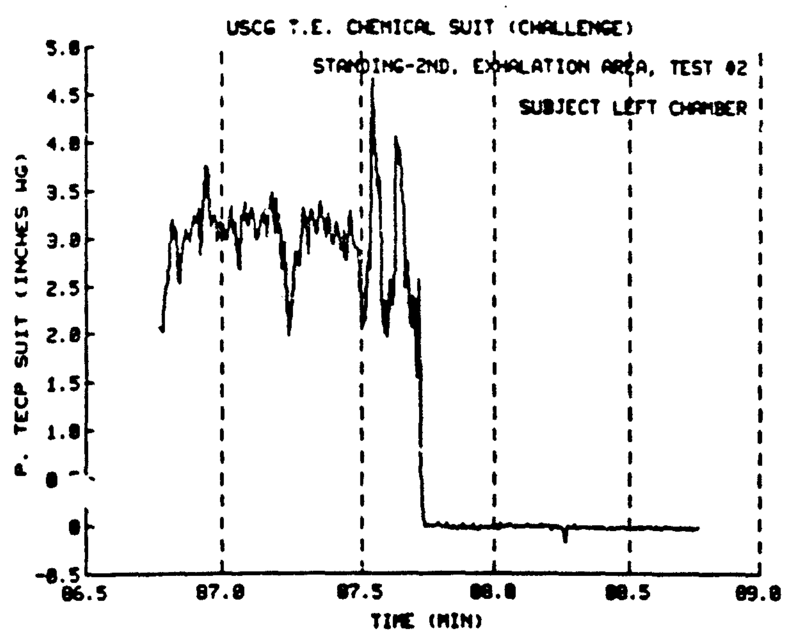
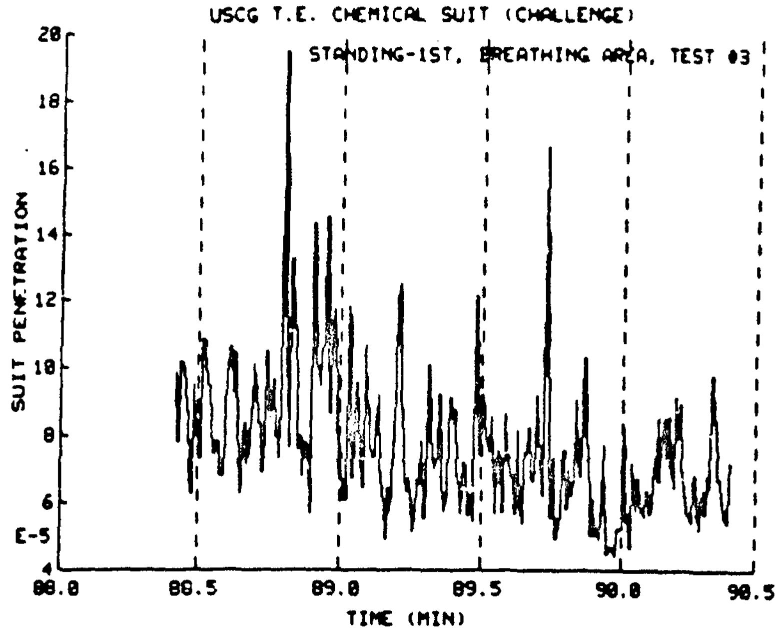


Figure 20. TECP suit aerosol penetration (VVZ) and pressure plots for standing in place.



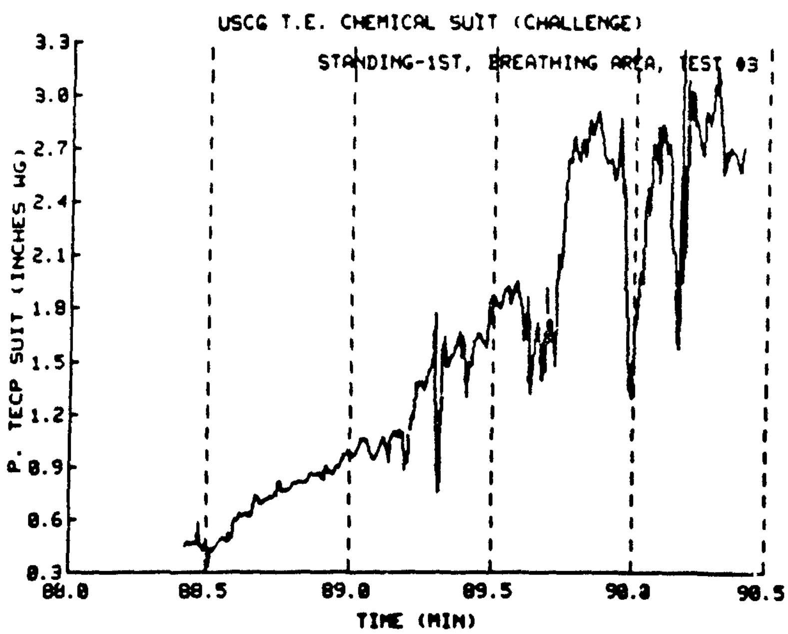
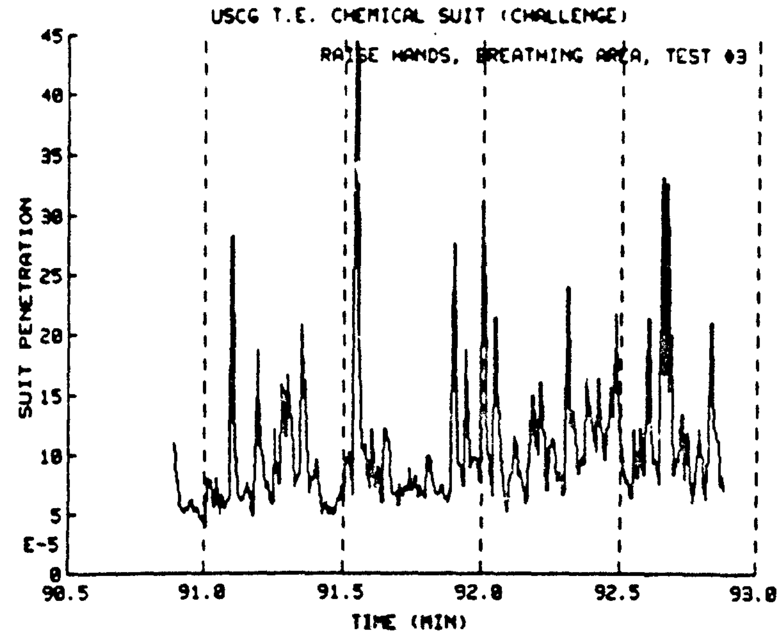


Figure 21. TECP suit aerosol penetration (BZ) and pressure plots for standing in place.



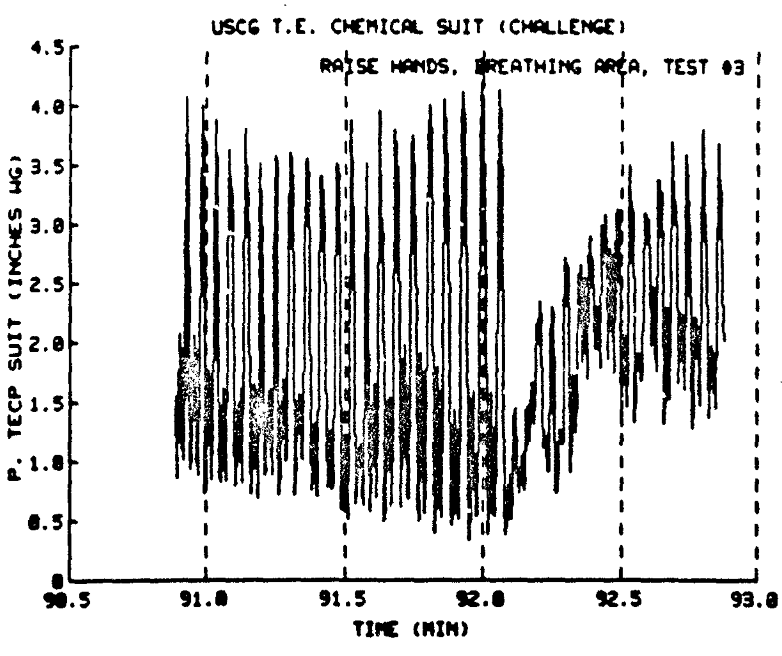
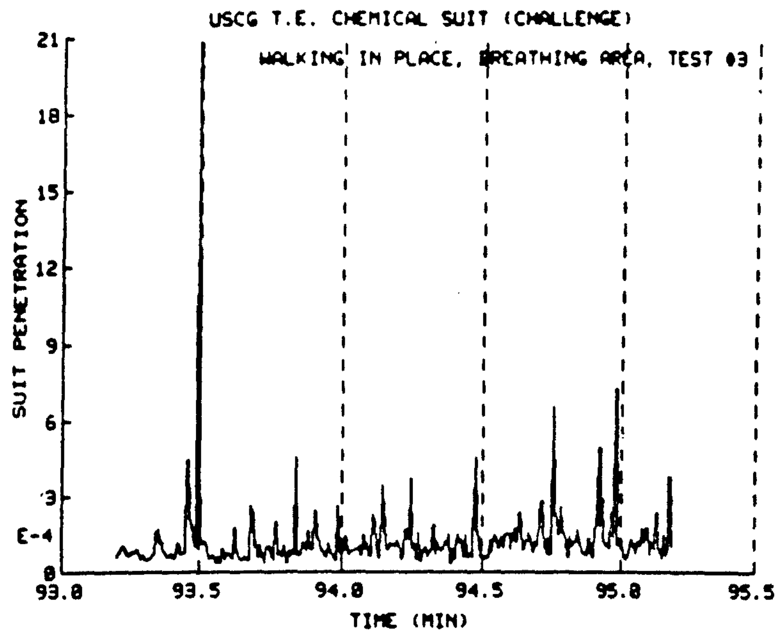


Figure 22. TECP suit aerosol penetration (BZ) and pressure plots for raising the hands above the head.



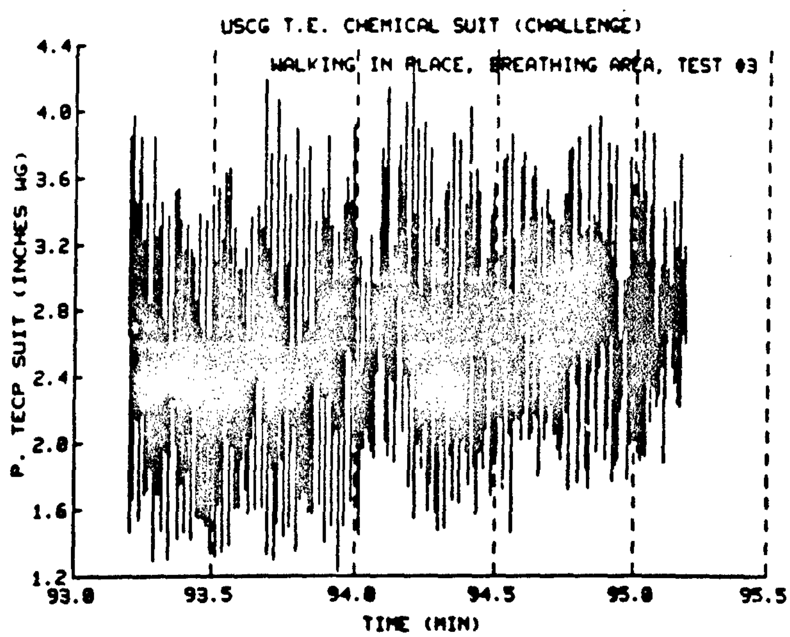


Figure 23. TECP suit aerosol penetration (BZ) and pressure plots for walking in place.

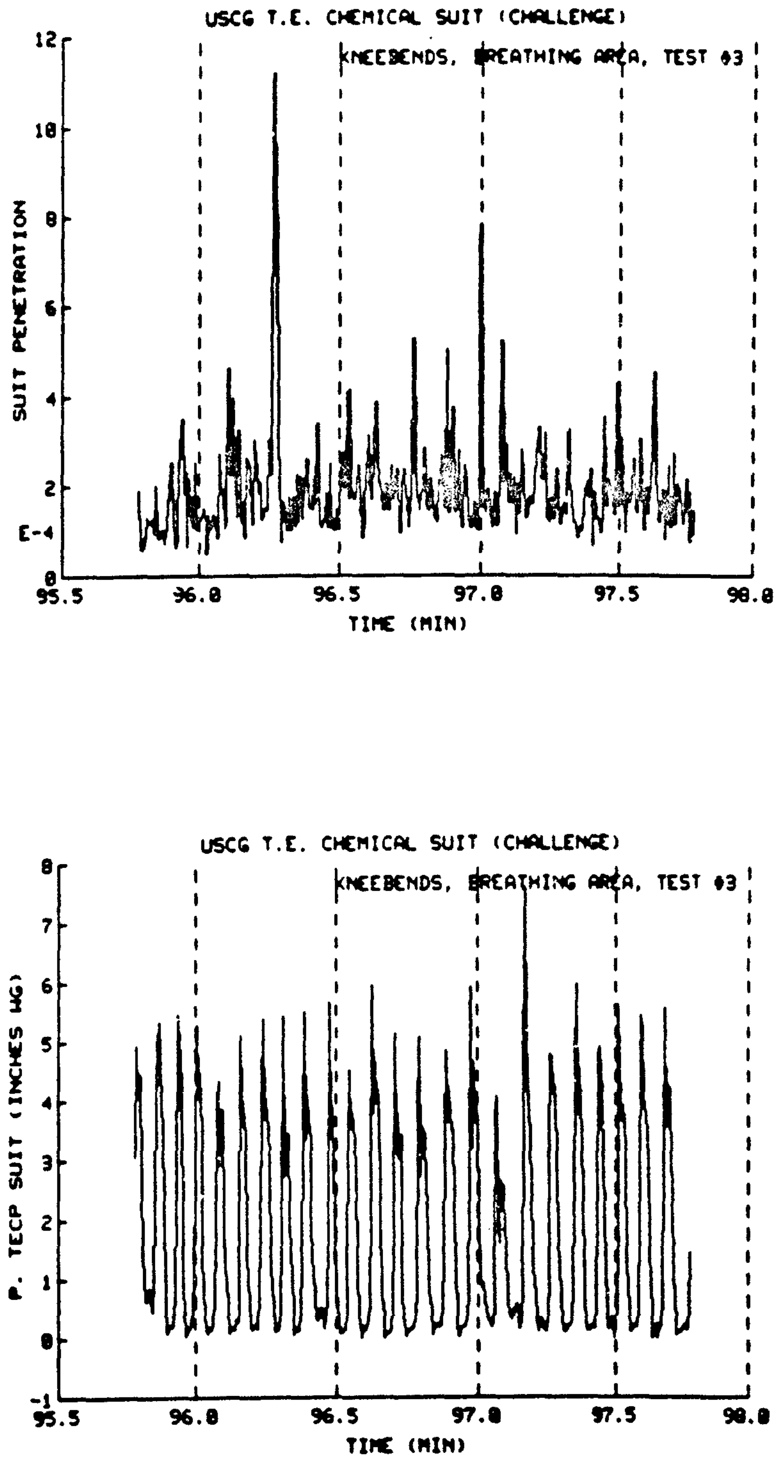


Figure 24. TECP suit aerosol penetration (BZ) and pressure plots during kneebends.

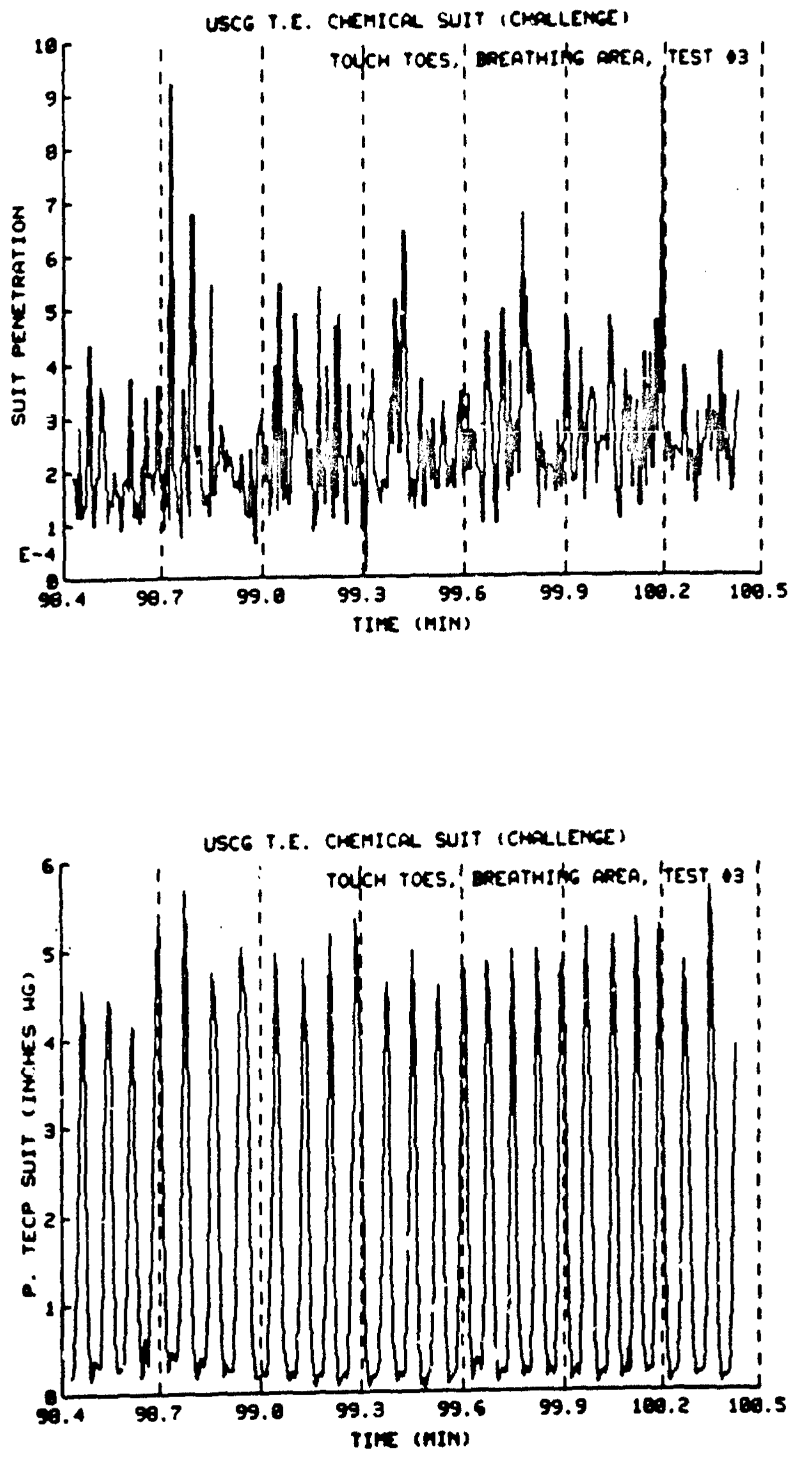
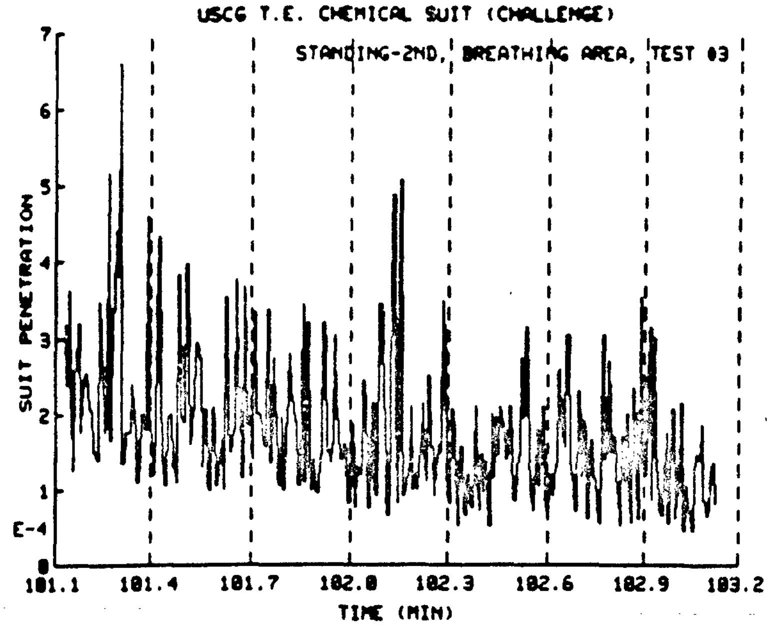


Figure 25. TECP suit aerosol penetration (BZ) and pressure plots for touching the toes.



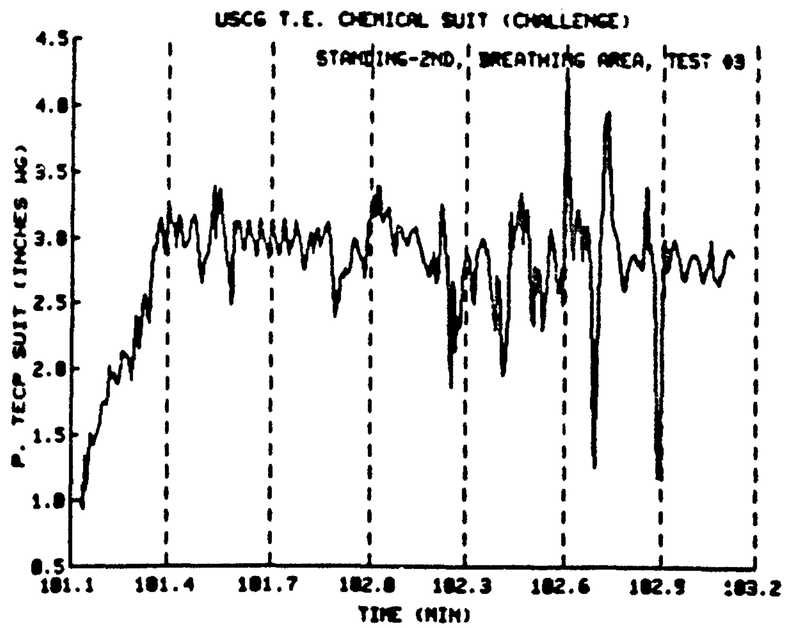
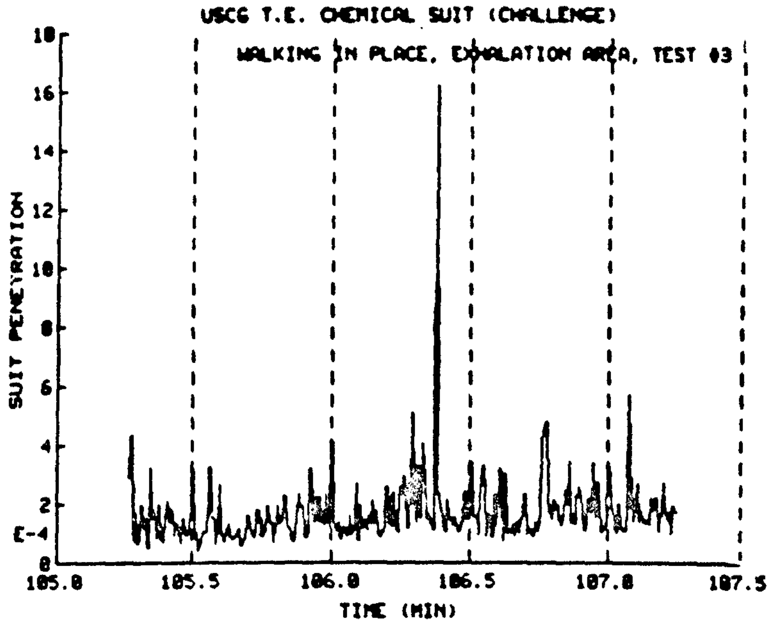


Figure 26. TECP suit aerosol penetration (BZ) and pressure plots for standing in place.



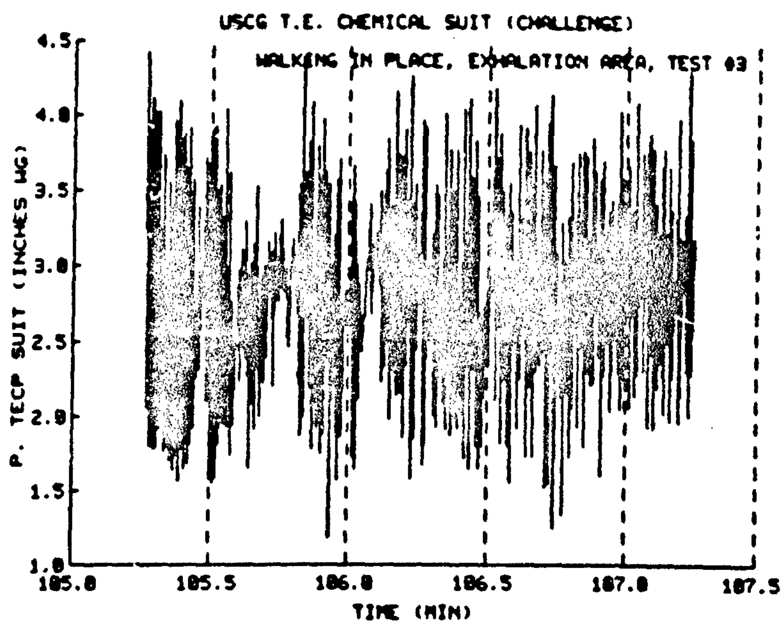
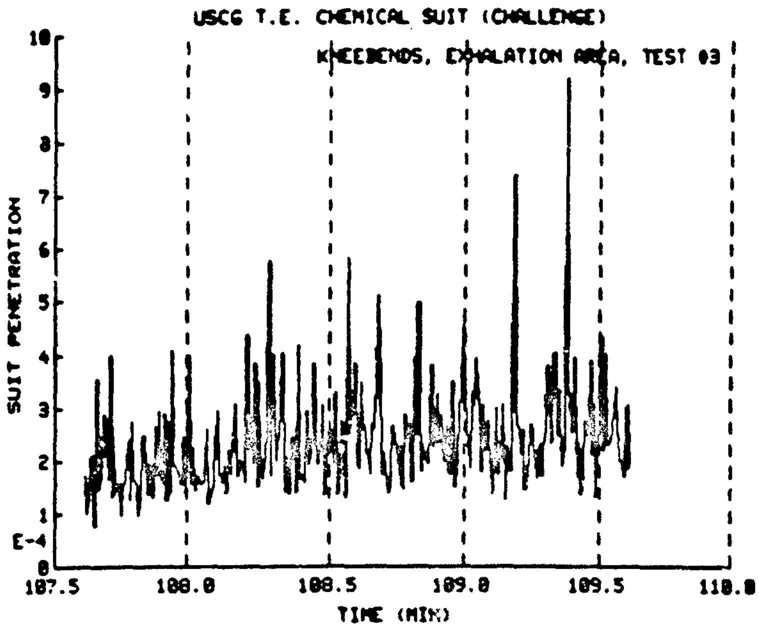


Figure 27. TECP suit aerosol penetration (VVZ) and pressure plots for walking in place.



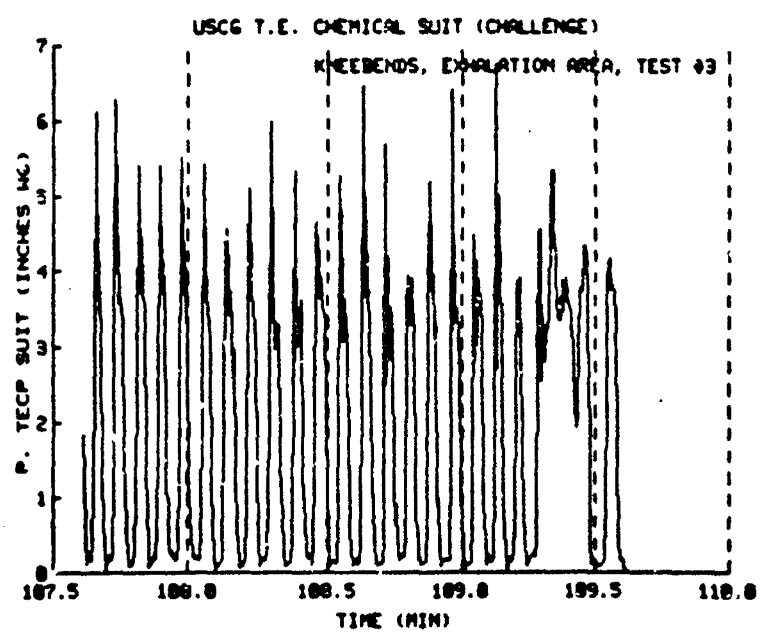
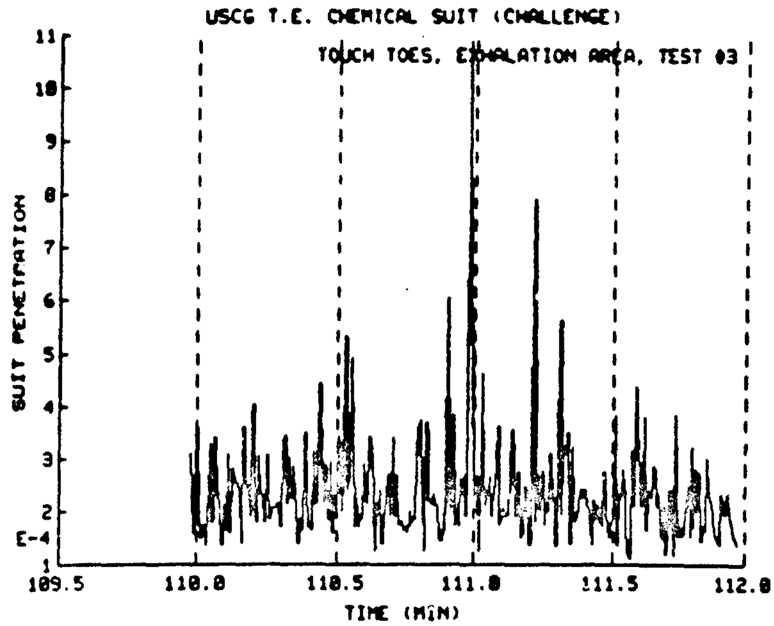


Figure 28. TECP suit aerosol penetration (VVZ) and pressure plots during kneebends



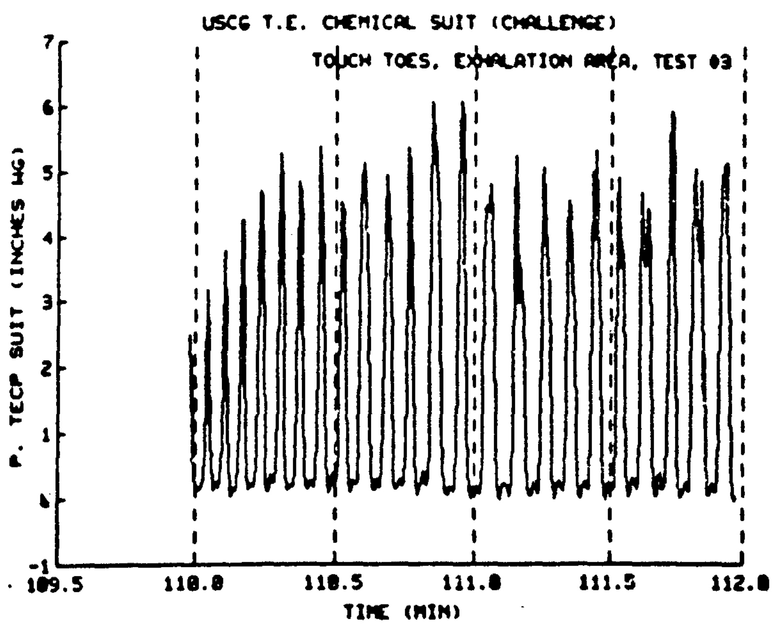


Figure 29. TECP suit aerosol penetration (VVZ) and pressure plots for touching the toes.

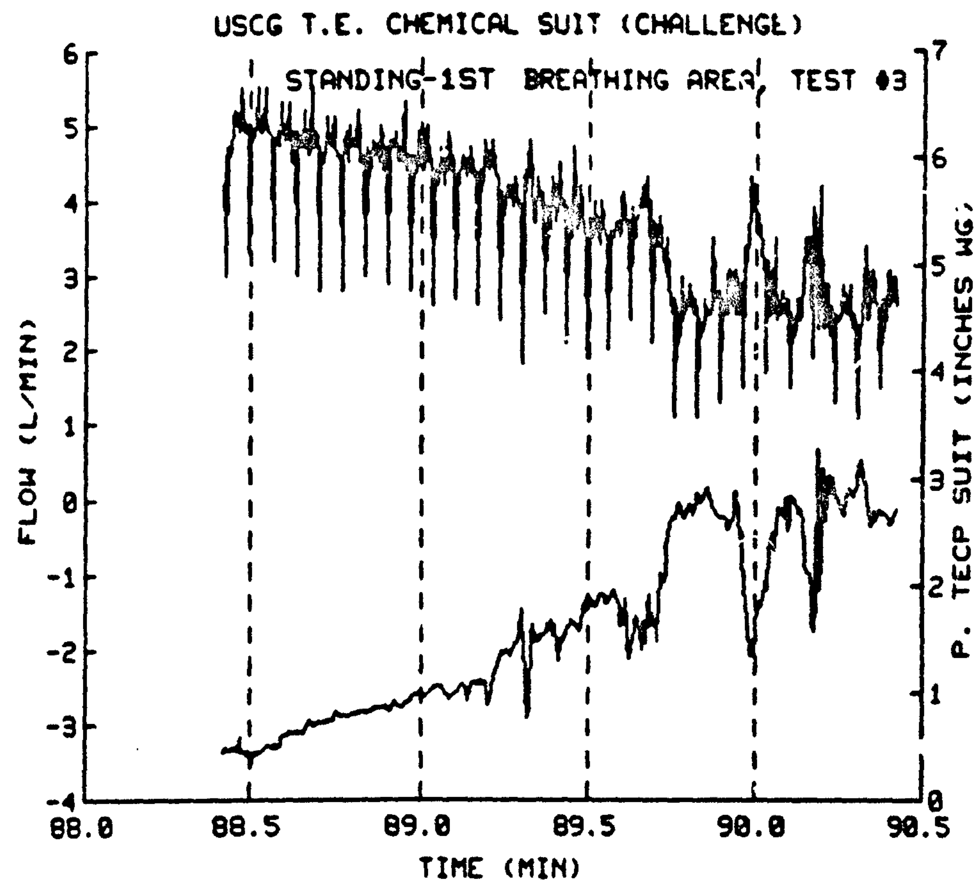


Figure 30. TECP suit pressure and flow plots for standing in place.

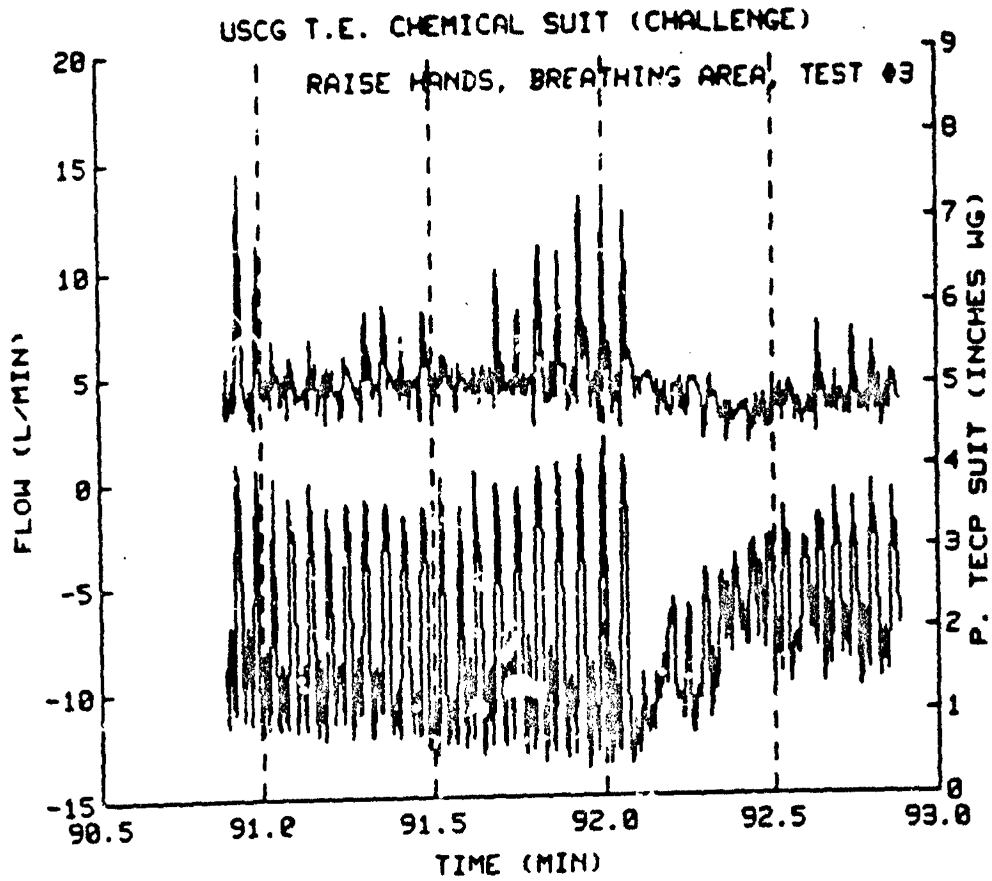


Figure 31. TECP suit pressure and flow plots for raising the hands.

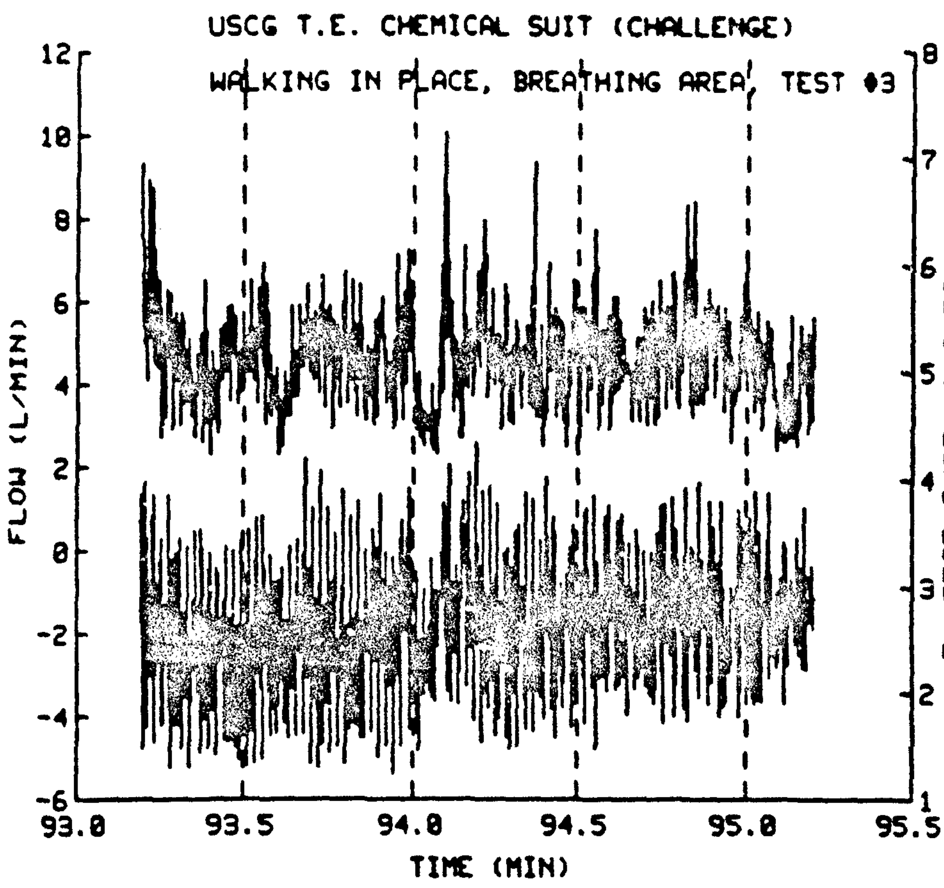


Figure 32. TECP suit pressure and flow plots for walking in place.

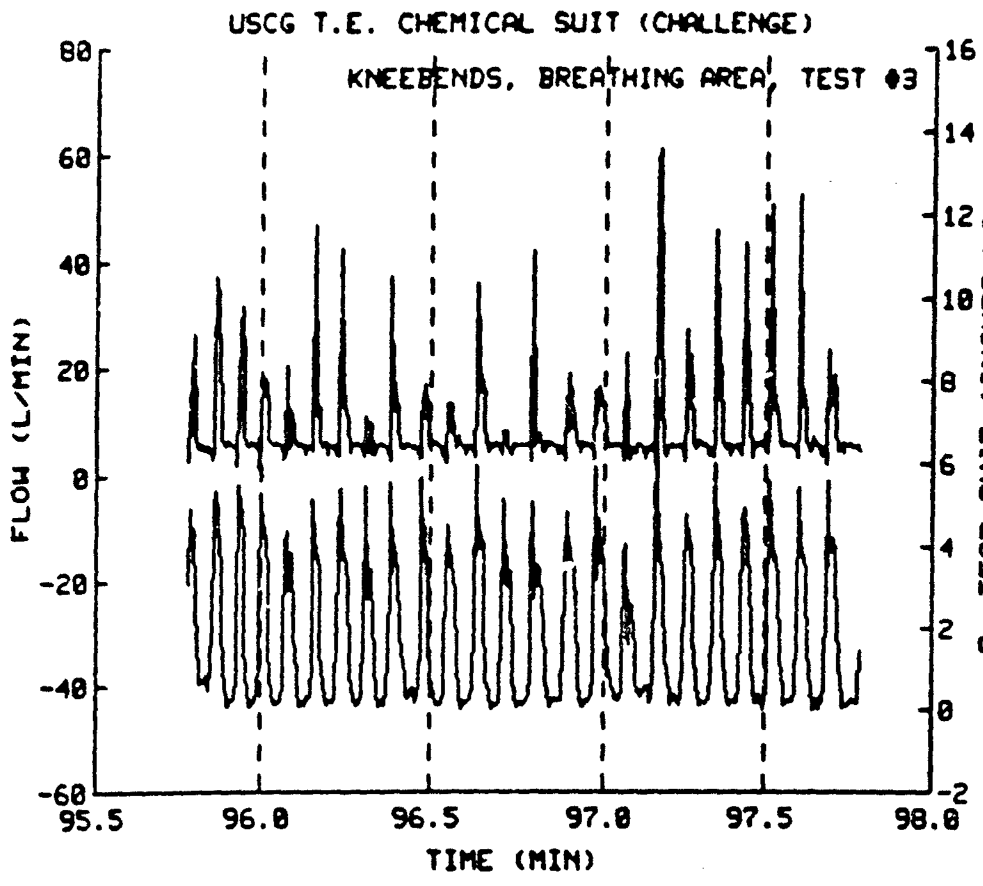


Figure 33. TECP suit pressure and flow plots during kneebends.

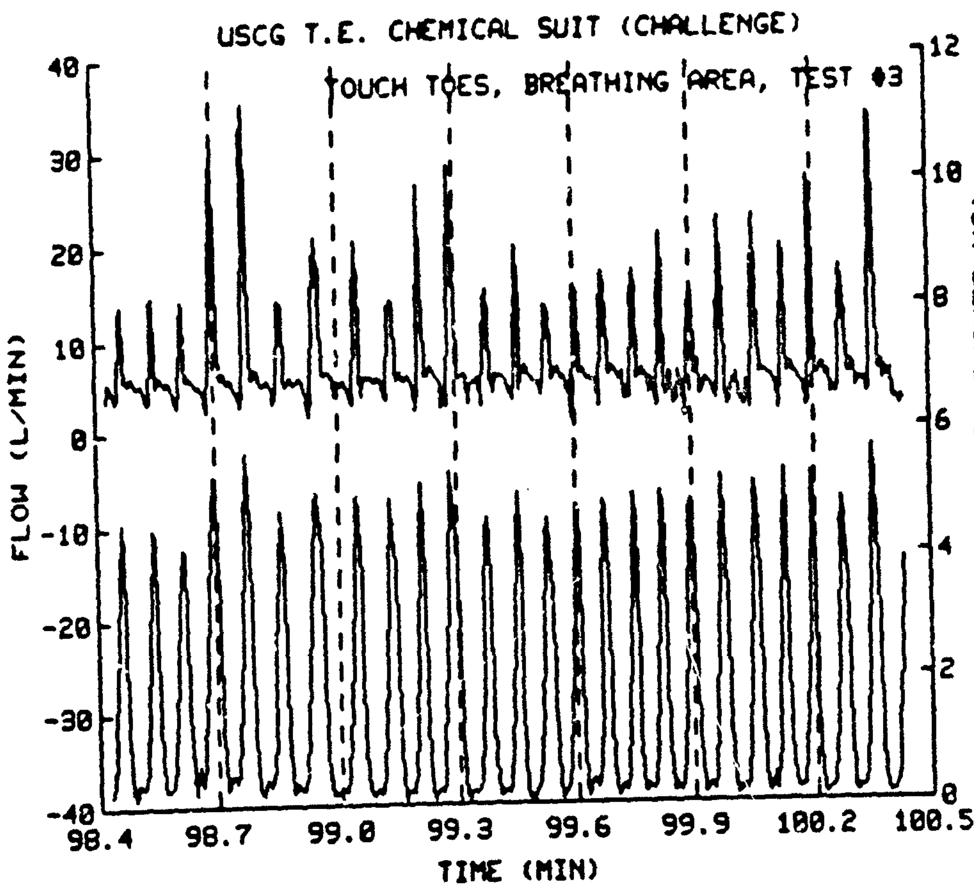


Figure 34. TECP suit pressure and flow plots for touching the toes.

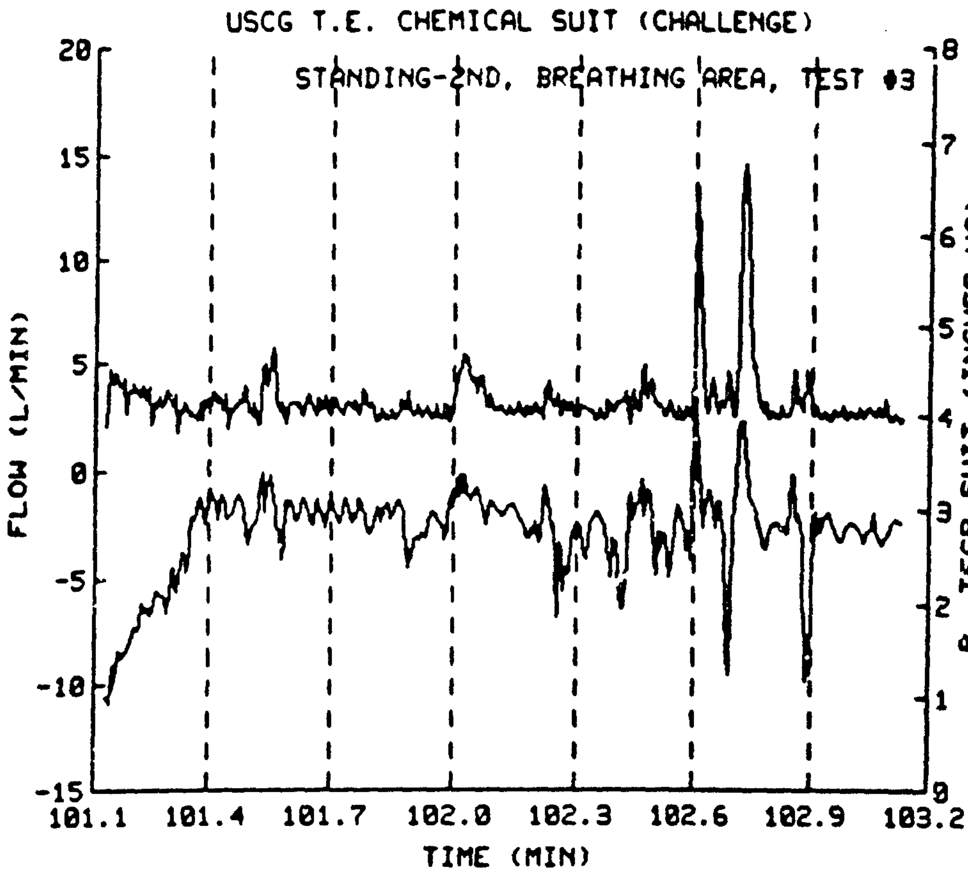


Figure 35. TECP suit pressure and flow plots standing in place.

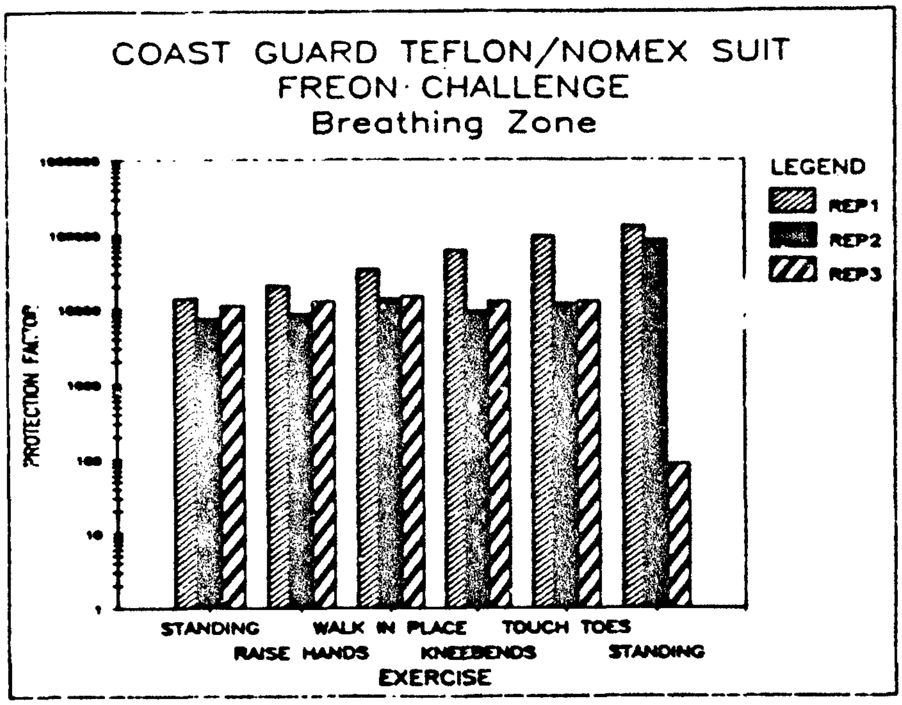


Figure 36. Bar chart showing achieved protection factors for various exercises while wearing the Coast Guard's Teflon[R]/Nomex[R] TECP suit and sampling in the breathing zone for Freon[R].

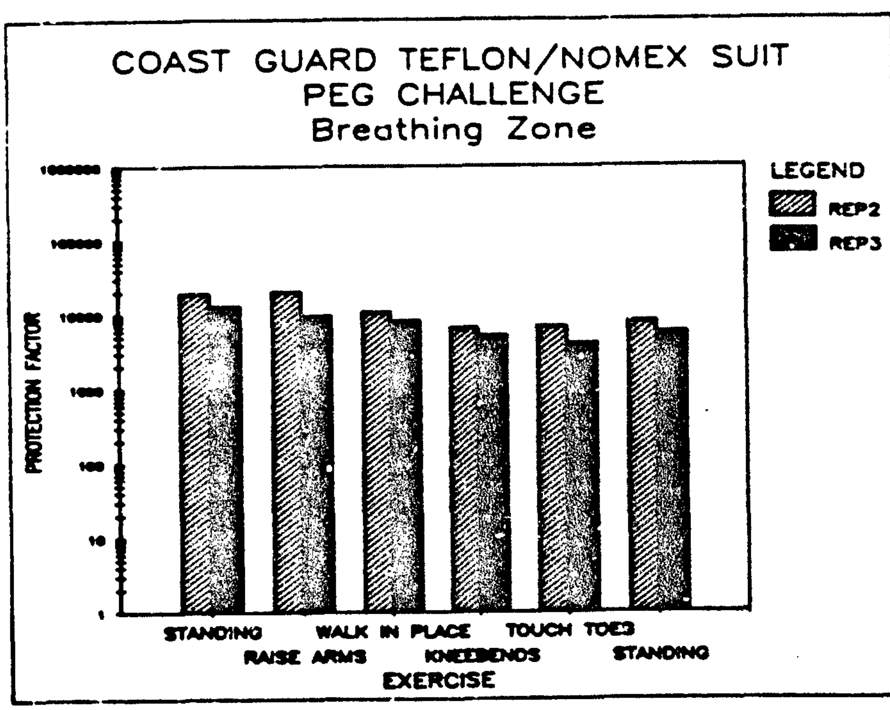


Figure 37. Bar chart showing achieved protection factors for various exercises while wearing the Coast Guard'sTeflon[R]/Nomex[R] TECP suit and sampling in the breathing zone for PEG 400.

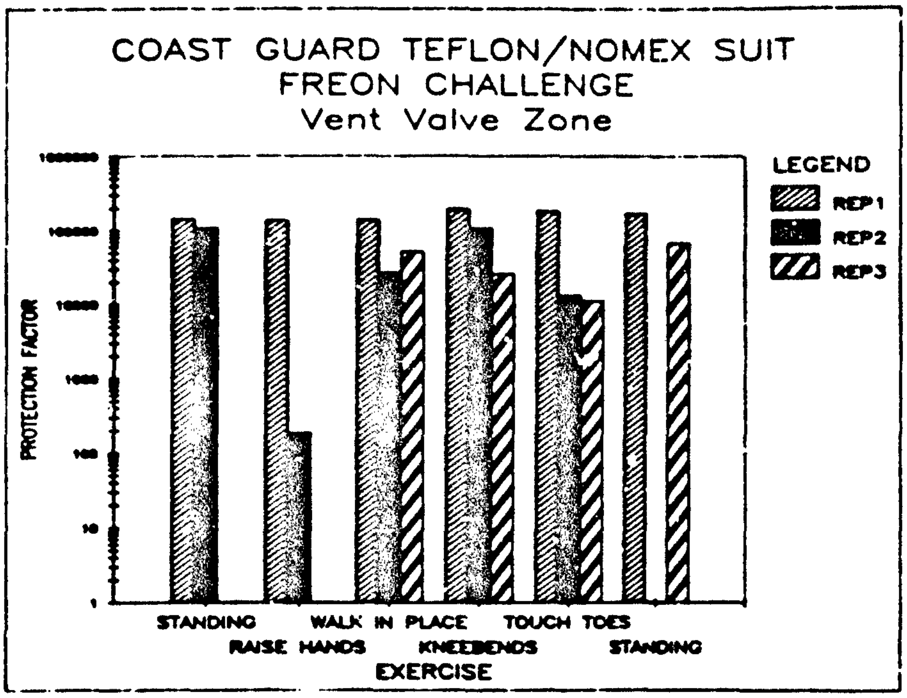


Figure 38. Bar chart showing achieved protection factors for various exercises while wearing the Coast Guard'sTeflon^{R}/Nomex^{R} TECP suit and sampling at the vent valve zone for Freon^{R}.

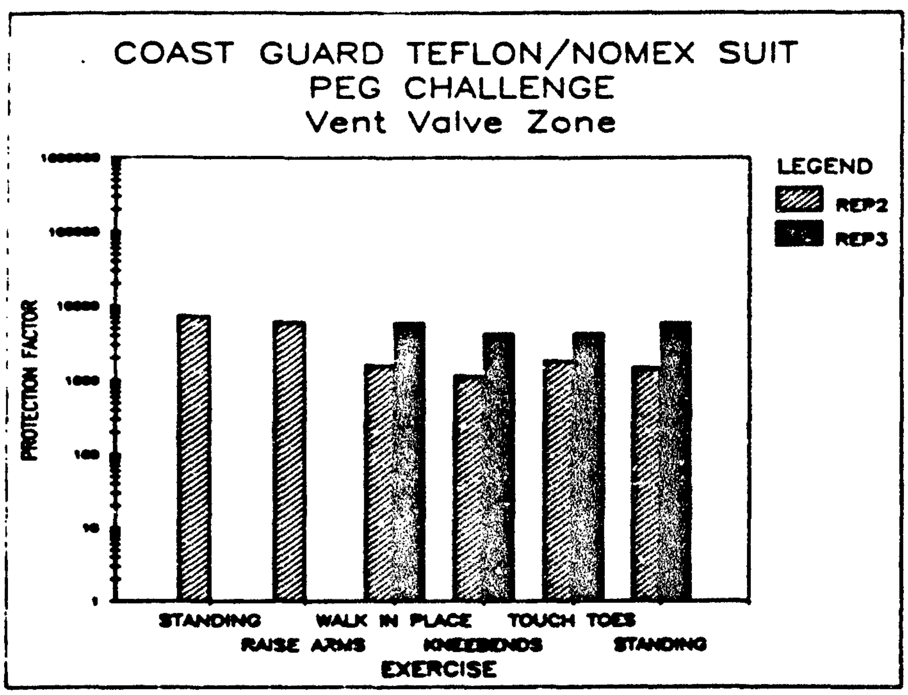


Figure 39. Bar chart showing achieved protection factors for various exercises while wearing the Coast Guard'sTeflon^{R}/Nomex^{R} TECP suit and sampling at the vent valve zone for PEG 400.

Table 1. Approximate internal suit pressure variation (positive inches water gauge) during man tests.

	Test 1		Test 2		Test 3	
	min	max	min	max	min	max
Standing	1.9	3.4	2.4	3.0	0.3	3.3
Raise hands	0.25	3.8	0.5	4.5	0.5	4.2
Walking in place	1.0	5.3	1.0	5.3	1.2	4.3
Knee bends	0.1	6.8	0.1	7.5	0.1	7.6
Touch toes	0.1	5.3	0.1	6.9	0.1	5.8
Standing	2.5	3.3	2.7	3.7	1.3	4.2
Standing	1.8	4.2	1.4	4.1	Not taken	
Raise hands	0.3	4.0	0.6	6.0	Not taken	
Walking in place	1.0	7.0	1.2	5.7	1.2	4.4
Knee bends	0.1	6.0	0.1	7.5	0.1	6.8
Touch toes	0.1	7.8	0.1	7.6	0.1	6.0
Standing	1.2	4.2	2.0	4.7	1.9	4.1
lowest min	(+) 0.1		(+) 0.1		(+) 0.1	
highest max		(+) 7.8		(+) 7.6		(+) 7.6

Discussion

The actual leak rate of TECP suits has not been measured accurately in hazardous material accidents. This lack of monitoring data is mainly due to the complicated and unanticipated nature of most accidents. To obtain a reasonable estimate of TECP suit performance in "HazMat" operations, a laboratory experiment has been designed to measure simulated TECP suit intrusion coefficients of the Coast Guard's new Teflon-coated Nomex suit. A man-test chamber equipped with both aerosol and gas leak-rate monitoring equipment was used. A series of light exercises designed to stress the various parts of the TECP suit was followed. The pressure inside the TECP suit was monitored continuously during the various exercises. The venting flow rate was also measured during one of the test runs.

Until this evaluation, no information has been available describing the variation in internal pressure and venting flow rate of a TECP suit during actual use. Table 1 summarizes the various pressure extremes in the suit. They range from + 0.1 to + 7.8 inches wg. which indicates that the positive-pressure vent valves do function as planned. The restrictions to movement due to suit tightness from being pressurized was found to be acceptable. The actual value of the positive pressure at reducing leak rates into the suit, is still unproven, however. This information was also useful background information for establishing the inflation pressures of ASTM's "Standard Practice for Pressure Testing of Gas-Tight Totally Encapsulating Chemical Protective Suits" (ASTM F 1052). It also provides a measure of the minimum strength suit materials, seams, and components must have. The venting flow rate, on the other hand, provides an accurate measure of the volume of air vented from the suit during the various exercises.

If one examines the plot of TECP suit pressure vs time for standing in place in Figs. 3, 5, 6, and 8, a measure of the positive pressure vent valve performance can be obtained. A rough average of the peaks produces an average cracking pressure of between 2.8 to 3.0 inches wg. The pattern is somewhat irregular because it is dependent on the breathing patterns of the human subject and body movements that depress the suit volume. The pressure plot for standing in place in Fig. 8 however, illustrates the relatively small operational range under which the valves can open and close (ΔP approximately 1/2 inch wg). Since there were three vent valves in the suit during this test series, one cannot identify pressure variations due to individual valve cracking pressure differences. It can be said qualitatively from the vent valve sounds that only one valve was venting most of the time, especially during the standing in place exercise. The need for more than one valve is also questionable from this observation and the corresponding pressure traces. The ability of the Stratotech one-way vent valve to operate at its adjusted cracking pressure of 2 inches wg is also questionable due to the 2.8 to 3.0 inches wg operational range that was observed throughout this experiment.

By comparing aerosol suit penetration vs time to the pressure variation vs time, a measure of the effect of suit leakage to pressure variation can be obtained. A careful review of Figs. 9 - 14 and 21 - 26 where aerosol penetration in the breathing zone vs time is compared to internal suit pressure vs time does not produce an obvious relationship. The lack of pressure vs leak rate relationship for the vent valve zone (VVZ) in Figs. 15 - 20 and 27 - 29 can also be seen. Additional experiments will have to be made on a more detailed basis before this relationship can be completely understood.

In Figs. 36 and 37 the average protection factors for the various exercises are illustrated as measured by Freon 12 and PEG penetration in the breathing zone area of the suit. A minimum of variability occurs between the two methods in this sampling area. This is indicative of good mixing of the challenge agents before they reach the sensors and general agreement with reference to the existence and magnitude of the TECP suit leaks. Since the Freon monitoring system uses grab samples to analyze, it can be expected to miss leak rate peaks, especially if they are short in duration.

The PEG monitoring system operates on a continuous basis and gives a better measure of the overall suit leak rate. The large variability between the protection factors as measured by Freon 12 and PEG is therefore understandable if the challenge agent occurs in pulses that are not mixed well. Thus a more accurate measurement of VVZ leakage is provided by the PEG system, which indicates the possibility of a significant leak from the vent valves. A more detailed evaluation of the leak rate of vent valves will be needed to determine if they present a significant leak source as they are used in the new Coast Guard TECP suit. This evaluation should examine valve performance during actual suit use and valve performance using a laboratory test fixture.

Conclusion

A series of test exercises have been carried out upon the new U.S. Coast Guard's Teflon-coated Nomex totally-encapsulating chemical protective (TECP) suit. The leak rate of this new TECP suit was measured using both an aerosol (PEG 400) and gas (Freon 12) during a prescribed series of test exercises. The internal suit pressure was also monitored and found to range from 0.1 to 7.8 inches of water gauge during the entire exercise series. This indicates that the positive-pressure vent valves do function as planned, and keep the TECP suit under a positive pressure. The need for more than one vent valve should be examined more closely, since it appeared that only one valve was operating in an effective manner during the three tests. Protection factor/intrusion coefficient valves for PEG 400 and Freon 12 within the breathing-zone area of the TECP suit were found to agree generally. Larger variations between the two challenge agents were found in the vent valve zone. This may be indicative of back streaming through the vent valves as venting takes place to relieve internal suit pressure. Additional studies to measure challenge concentrations inside the suit at various sampling locations are necessary to better quantify this preliminary observation. Laboratory experiments measuring the leak rates of TECP suit vent valves in an isolation test fixture are also necessary to better understand valve performance.

APPENDIX A

TECP SUIT TEST PROTOCOL

for

USCG/USFA PROJECT

Safety Science Group

Special Projects Division

Hazards Control Department

Lawrence Livermore National Laboratory

Introduction

The need to provide complete encapsulation of workers to allow them to carry out their jobs safely is becoming very commonplace. Such jobs as hazardous material response, toxic waste dump cleanup, and chemical manufacture and use require complete encapsulation of employees routinely or during accidents. With the increase use of complete encapsulation in the workplace, a high degree of performance is now expected from commercially available totally-encapsulating chemical protective (TECP) suits. This high degree of performance was also identified by John B. Moran, Head, Division of Safety Research, National Institute for Occupational Safety and Health, when he referred to chemical protective clothing as "the last line of defense" for the worker.

A TECP suit is made up of many components (Fig. 1). Many of these components are in themselves individual items of chemical protective clothing for which chemical permeation data is available. Some items however, such as suit closures, vent valves, lens material, suit membranes, and seams are unique to a TECP suit and therefore require individual chemical permeation testing. This type of data however, does not provide the user with a measure of complete TECP suit integrity. To measure the complete integrity and performance of TECP suits, quantitative chamber testing can be used. By simultaneously using both an aerosol and gas test agent one can determine the TECP suit leak rate accurately. If these measurements are made while the suit is being worn by a person performing a series of exercises, a good estimate of field TECP suit performance can be obtained.

Experimental Setup

To measure TECP suit leak rates accurately separate gas (Freon[R] 12) and

aerosol polyethylene glycol molecular weight 400 (PEG 400) detection systems will be used. The Freon[R] 12 subsystem uses a man-test chamber concentration of 1000 ppm as determined by a Wilks Model 1A infrared spectrophotometer. The interior of the TECP suit is monitored for Freon[R] 12 intrusion using a Varian Model 2700 gas chromatograph (GC) equipped with an electron capture detector (ECD). Since the GC/ECD detection limit for Freon[R] 12 is 0.01 - 0.001 ppm, this measurement technique enables one to measure an intrusion coefficient of 100,000 to 1,000,000. A gas sampling valve is used to collect discrete samples from the interior TECP suit air approximately every two minutes.

To measure the aerosol concentrations in the man-test chamber (Fig. 2) and within the TECP suit a Phoenix Precision Instrument's Model JM 7000 forward light scattering photometer will be used. The test aerosol of PEG 400 will be generated using a Laskin nozzle generator which creates a mass median aerosol diameter aerosol of approximately 0.68)m, sg = 2.10. Aerosol concentrations within the man-test chamber will be 25 ± 5 mg/M^3. A sample of two liters per minute is withdrawn from the suit and passed through the photometer providing a real time measure of aerosol concentrations within the suit.

Sample line penetrations into the TECP suit will take advantage of existing penetrations for uch things as airline cooling or communication. If these types of penetrations are not available a cuff ring with sampling port will be attached using a removable glove connection. If these methods are not applicable a hole will be cut in the suit and a sampling line will be sealed into the suit. The last method is the least desirable but necessary when no other sampling line penetration is available. The minimum number of connections necessary to connect the sampling line to the proper monitoring instrument will be used with a minimum length of sampling line. During a

typical test, samples of both Freon[R] 12 and PEG 400 will be taken simultaneously and used to determine TECP suit performance.

A series of light exercises have been chosen to stress the suit in a manner similar to typical work routines. Each exercise is carried out for two minutes completing the prescribed number of repetitions.

- Stand in place.

- Raise hands from waist to above the head, completing at least 15 raising motions per minute.

- Walk in place completing at least 15 raising motions of each leg per minute.

- Touch the toes, making at least 10 complete motions of the arms from above the head to the toes per minute.

- Perform deep knee bends, making at least 10 complete standing and squatting motions per minute.

- Repeat complete exercise series.

- Exit man-test chamber.

The exercise series requires approximately 20 minutes plus donning and doffing time. A 30-minute SCBA bottle will work some of the times, but a 60-minute bottle is preferred.

Two USCG/USFA TECP suits will be evaluated along with single suits from four commercial manufacturers.

Data Analysis

The output from the photometer, GC/ECD and infrared spectrophotometer will be collected on a DEC LSI 11/23 lab computer. Suit intrusion coefficients[1] will be calculated for both aerosol and Freon^{R} 12 test agents and their results compared. Graphs showing these intrusion coefficients will be included in the final report.

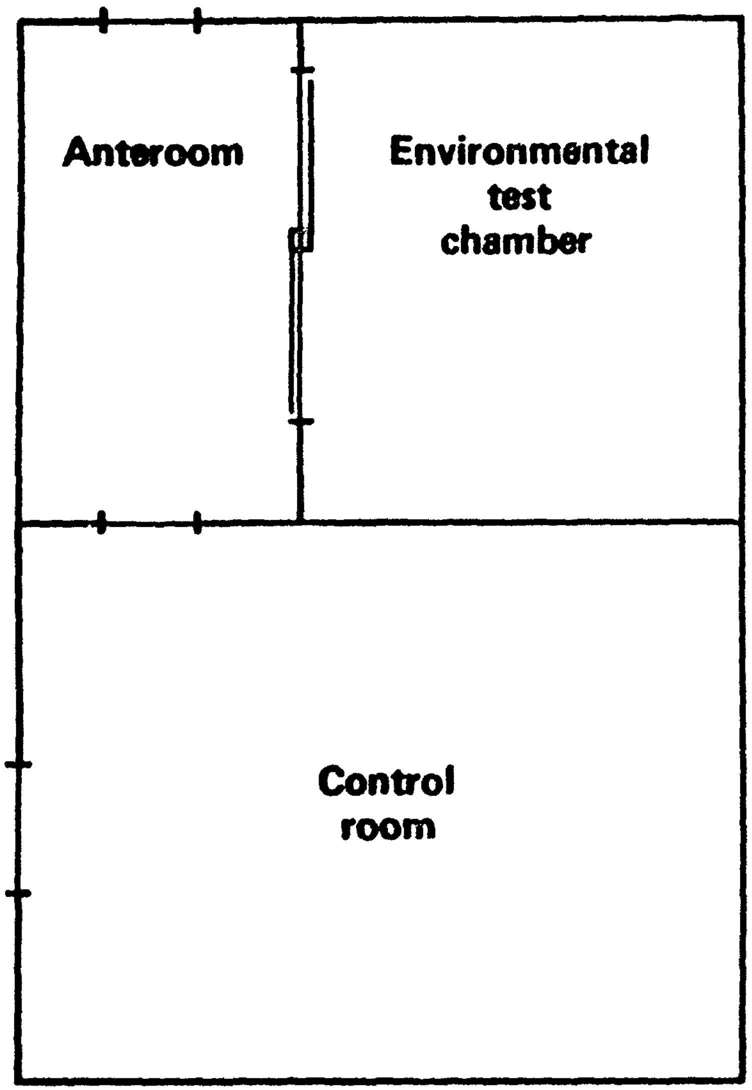
To determine if various components of the TECP suit are leaking the internal samplings lines will be placed in close proximity to the component in question.

Final Report

A final report will be prepared summarizing the results of the various TECP suits along with any conclusions with reference to specific suit component performance.

[1] Intrusion Coefficient = $\frac{\text{Outside Concentration}}{\text{Interior Suit Concentration}}$

Safety science group environmental test facility



Test atmospheres:
- Freon™ 12 (gas)
- PEG 400 (aerosol)

Stress testing:
- Treadmill

Monitoring:
- GC with electron capture detectors
- IR
- Photometer
- Optical particle sizer
- Size/charge particle counter
- Humidity monitor
- Air flow monitor
- Pressure monitor
- Heart rate monitor

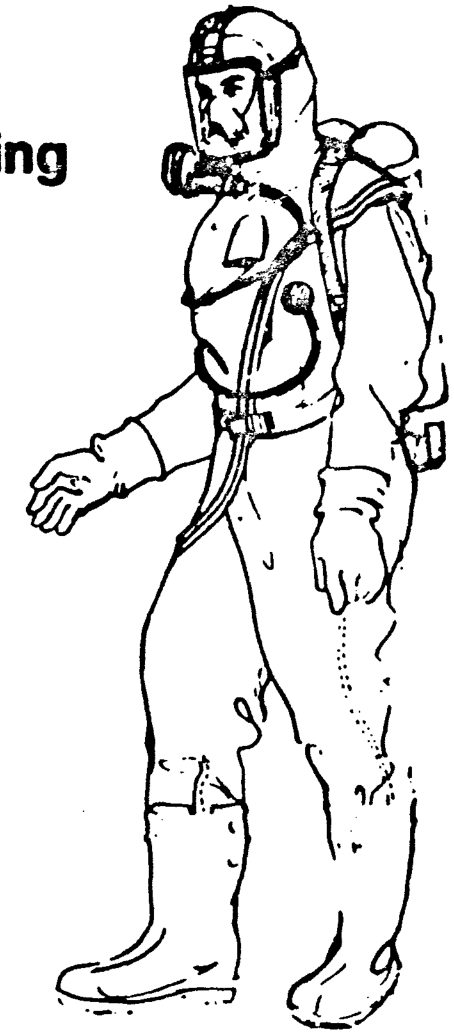
Computer interface:
- DEC LSI 11/23

Figure 2. Safety Science Group man-test chamber layout and monitoring equipment.

Suit Design

- Self-contained breathing apparatus (SCBA)
- Lens
- Suit closure
- Vent valves
- Suit membrane
- Seams
- Gloves
- Boots

Type I



Type II

Figure 1. The configuration and design of Type I and Type II totally-encapsulating chemical-protective suits.